THE GEOLOGY AND PRODOCTION HISTORY OF THE URANIUM - VANADIUM DEPOSITS IN THE LUKACHUKAI MOUNTAINS, APACHE COUNTY ARIZONA

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THE GEOLOGY AND PRODUCTION HISTORY OF THE URANIUM - VANADIUM DEPOSITS IN THE LUKACHUKAI MOUNTAINS, APACHE COUNTY ARIZONA

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ABSTRACT

Uranium-vanadium deposits have been discovered and mined in the Lukachukai Mountains, a high, rugged northwest spur of the Chuska Mountains in northeastern Arizona. All of the economic deposits are in the Salt Wash Member of the Morrison Formation of Jurassic age. Ore bodies occur some 30 to 80 feet above the base of the Salt Wash which is roughly the middle half of the member. All of the significant deposits are located in a well-defined belt which trends nearly north-south across the southeast end of the mountains. This belt accounts for 99.6 percent of the total production and includes an area of 6.5 square miles. The ore bodies are elongate and horizontally lenticular in shape and consist of one or more ore pods surrounded or separated by protore. The composite length of ore bodies consisting of two or more ore pods separated by protore ranges up to 1,100 feet; individual ore pods range up to 350 feet in length. The length is usually at least three times the width and is parallel to paleostream depositional trends measured in and near the ore bodies. Thicknesses of the ore bodies range from 1 to 22 feet. Claystone and/or siltstone beds nearly always underlie and frequently overlie the host sandstone units.

Ore occurs most commonly in trough-type, cross-stratified sandstone which fills scours and channels in the underlying claystone. Lithofacies maps and mine mapping show that ore bodies are restricted to areas of rapid lateral color change which, in general, are also areas of rapid change in the ratio of mudstone to sandstone. It is common for the elongation of ore pods to deviate from the paleostream depositional trend and parallel the prominent joint set. This feature suggests some redistribution of the ore.

Tyuyamunite, the calcium uranium vandate, is the most common ore mineral. It occurs irregularly disseminated, concentrated in lenses, or distributed in bands. It may fill the sand interstices, or only coat sand grains, or it may replace calcite and carbon.

Due to the remoteness of the mountains, the deposits were not discovered until 1949. Since this was a new district in the Salt Wash, the U.S. Atomic Energy Commission was interested in developing the uranium resources of the area. Between September 1950 and August 1955, 1,835 holes with a total footage of 374,198 feet were drilled in the Lukachukai Mountains. This drilling was highly successful and greatly aided mining companies in developing minable ore reserves.

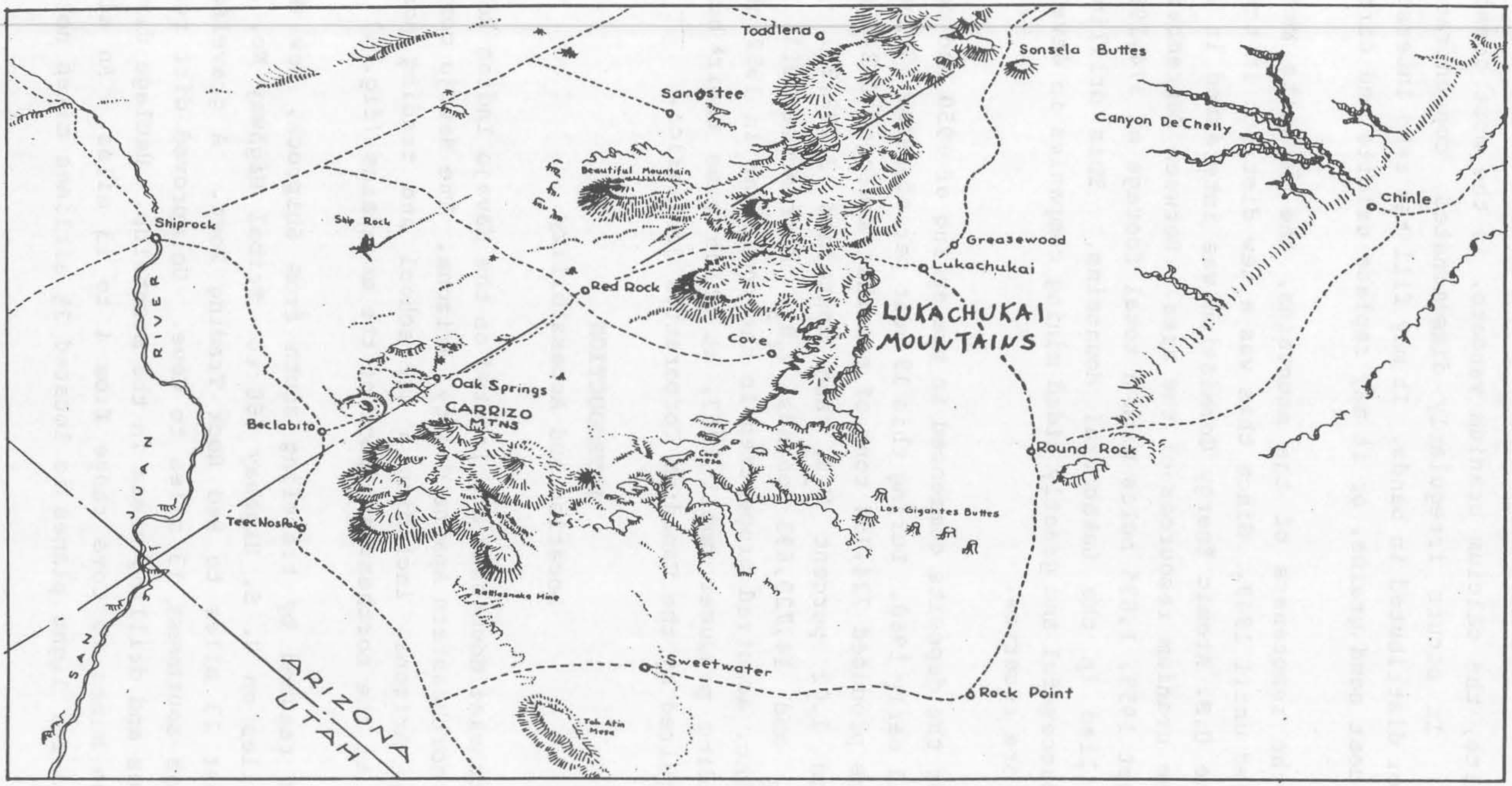
Mining of the deposits commenced in the spring of 1950 and continued until early 1968. During this 19 year period, some 53 individual mines produced 724,754 tons of ore that averaged 0.24 percent U_3O_8 and 1.02 percent V_2O_5 and contained 3,483,231 pounds of U_3O_8 and 14,729,693 pounds V_2O_5. Kerr-McGee Oil Industries, Inc. acquired properties in the mountains in 1952 and was the leading producer until 1963, at which time their holdings were acquired by the Vanadium Corporation of America.

INTRODUCTION

Location And Accessibility

The Lukachukai Mountains are located on the Navajo Indian Reservation in northeastern Apache County, Arizona. The Navajo community of Cove, Arizona, including a day school and trading post, is located at the northeastern foot of the mountains (fig. 1).

Cove is reached by traveling south from Shiprock, New Mexico, seven miles on U. S. Highway 666 to Tribal Highway No. 13 and then west 23 miles to Red Rock Trading Post. A graveled road continues southwest 13 miles to Cove. Unimproved dirt roads to the mines and drilling areas in the mountains. Haulage distances from the mines to Cove range from 4 to 13 miles. An airstrip suitable for light planes is located 2½ airlines miles northeast of Cove.



Sketch of the Four Corners region showing
the location of the Lukachukai Mountains.
Kenneth G. Hatfield, 1953.

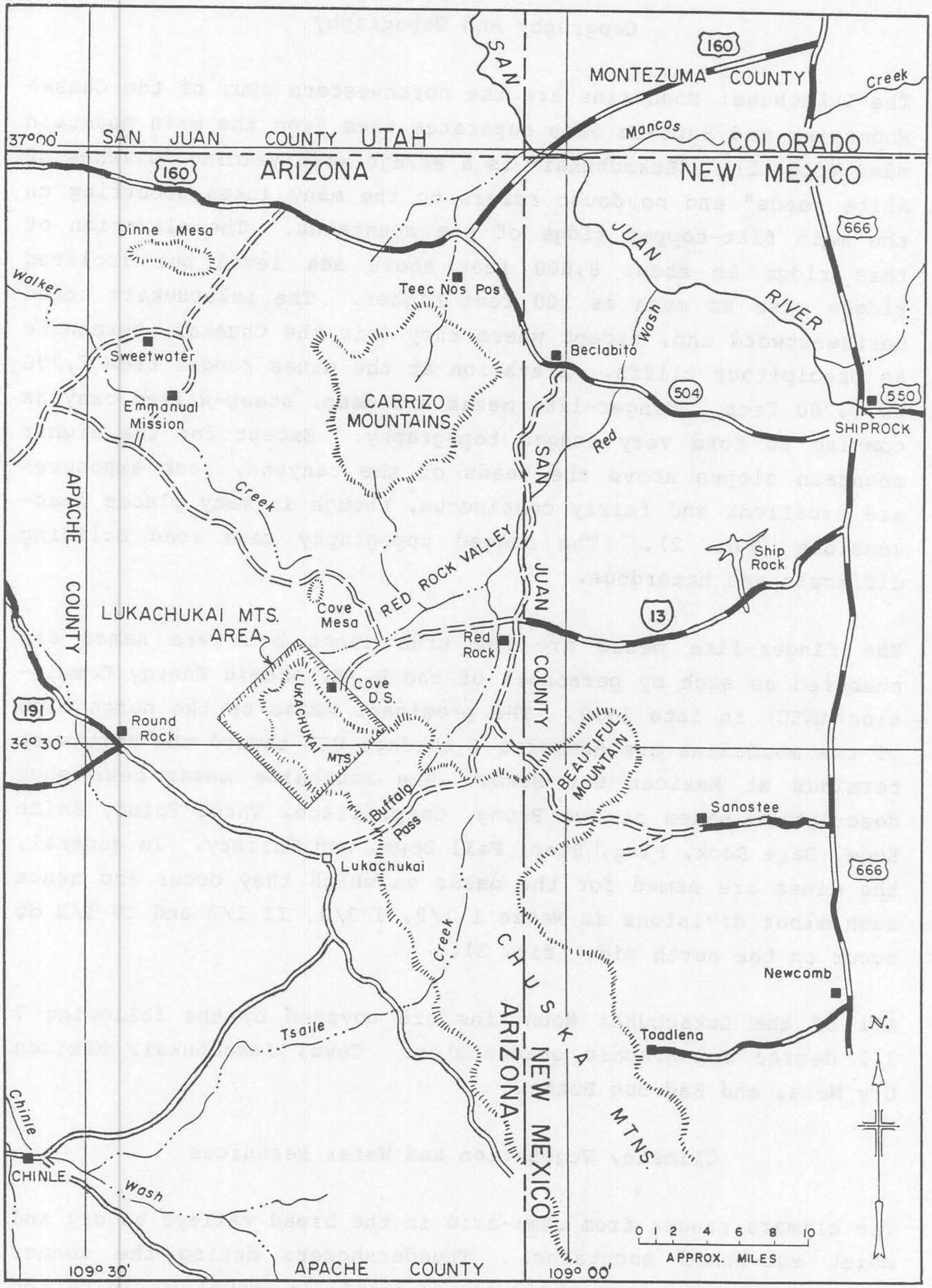


Figure 1. Index map of the Four Corners Region

Geography And Topography

The Lukachukai Mountains are the northwestern spur of the Chuska Mountains and Buffalo Pass separates them from the main mountain mass (fig. 1). "Lukachukai" is a Navajo word meaning "patches of white reeds" and no doubt refers to the many lakes occurring on the main flat-topped ridge of the mountains. The elevation of this ridge is about 8,800 feet above sea level but isolated ridges rise as much as 100 feet higher. The Lukachukais trend northwestward and, except where they join the Chuskas, terminate as precipitous cliffs. Elevation at the mines ranges from 7,200 to 7,700 feet. Finger-like mesas and deep, steep-walled canyons combine to form very rugged topography. Except for the higher mountain slopes above the heads of the canyons, rock exposures are excellent and fairly continuous, though in many places inaccessible (fig. 2). The rugged topography made road building difficult and hazardous.

The finger-like mesas are not true mesas but were named and numbered as such by personnel of the U. S. Atomic Energy Commission (AEC) in late 1950. The prominent mesas on the north side of the mountains are numbered I through VII toward the northwest terminus at Mexican Cry Mesa. The southside mesas bear such descriptive names at Two Prong, Camp, Cisco, Three Point, Knife Edge, Bare Rock, Flag, Step, Fall Down, and Thirsty. In general, the mines are named for the mesas on which they occur and hence such minor divisions as Mesas I 1/2, I 3/4, II 1/2 and IV 1/2 do occur on the north side (fig. 3).

All of the Lukachukai Mountains are covered by the following 7 1/2 degree topographic quadrangles: Cove, Lukachukai, Mexican Cry Mesa, and Bad Bug Butte.

Climate, Vegetation and Water Resources

The climate ranges from semi-arid in the broad valleys to dry and moist sub-humid mountains. Thundershowers during the summer months account for most of the annual rainfall; annual precipitation

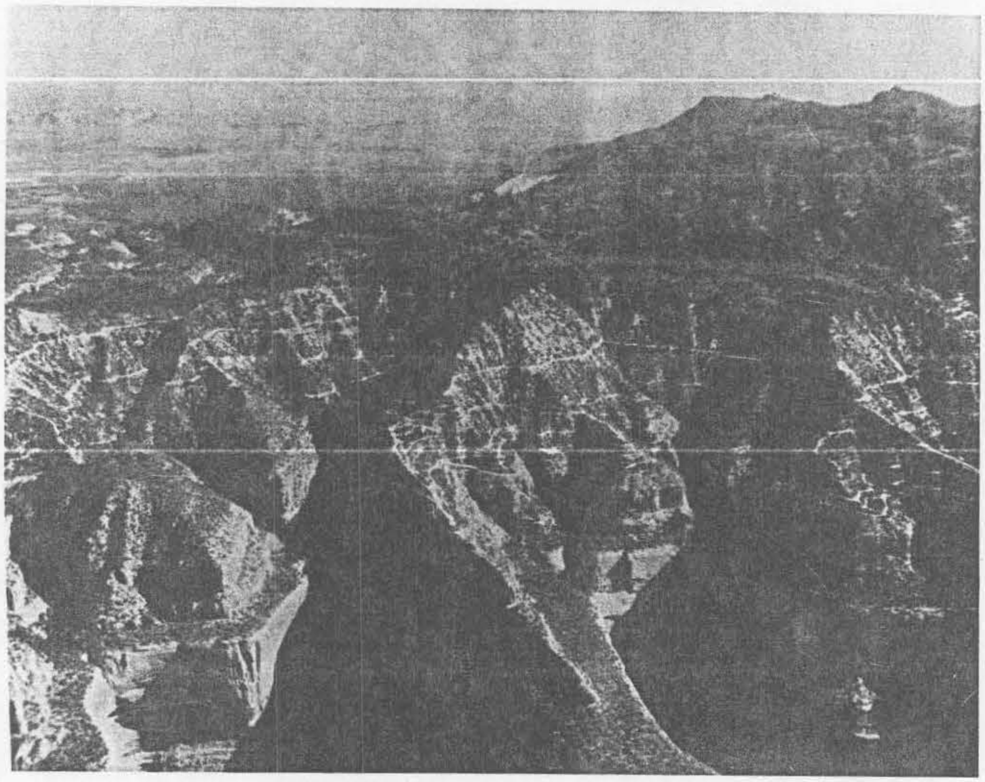


Figure 2. Aerial view looking northeasterly across the Lukachukai Mountains showing AEC drill roads and mine access roads. Flag Mesa is the prominent feature in the lower center of the photo. Step Mesa is in the lower left and Bare Rock Mesa is at the right. The Flag No. 1 Mine is near the tip of the mesa. Photograph by W. L. Chenoweth, 1957.

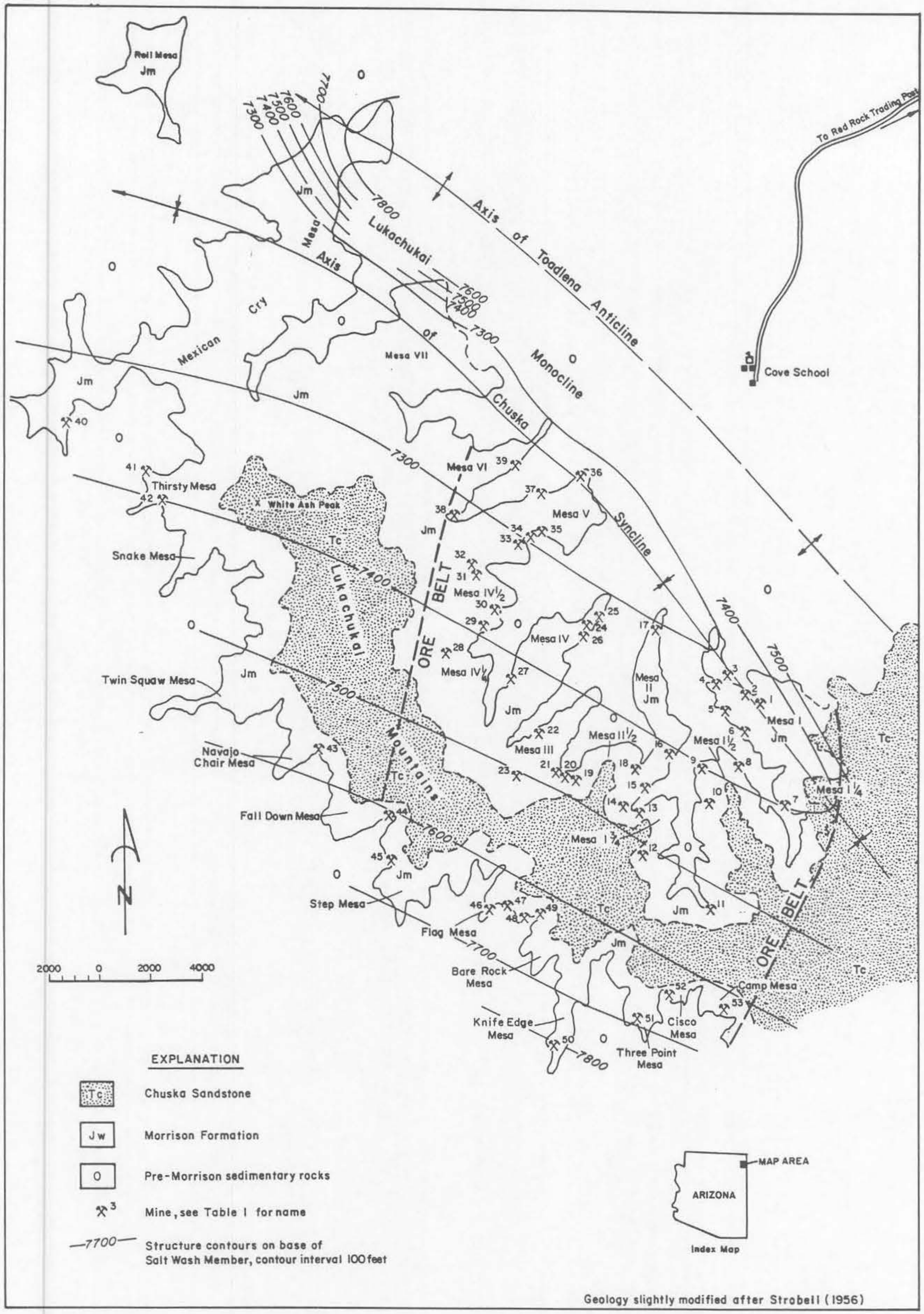


Figure 3. Mine location map Lukachukai Mountains, Apache County, Arizona

Table 1
Names of mines shown on figure 3

No.	Name	No.	Name
1	Mesa I, Mine No. 13	28	Mesa IV 1/4
2	Mesa I, Mine No. 10	29	South Portal, Frank No. 1 (4B)
3	Mesa I, Mine No. 15	30	East Portal, Frank No. (709)
4	Mesa I, Mine No. 11	31	North Portal, Frank No. 1 (1207)
5	Mesa I, Mine No. 12	32	Mesa IV 1/2 (1212)
6	Mesa I, Mine No. 14	33	Mesa V
7	Mesa I 1/4	34	Mesa V Adit (Mine 1)
8	Mesa I 1/2	35	Mesa V Incline (Mine 2)
9	Henry Phillips	36	Cato No. 1 Pit
10	Mesa I 1/2 West	37	Frank Junior (Cato No. 1)
11	Billy Topaha	38	Mesa VI
12	Mesa I 3/4 Incline	39	Cato No. 2
13	Mesa I 3/4, Mine No. 2, P-150	40	Mexican Cry (Tom Nakai Chee)
14	Mesa II, Mines 1 & 2, P-21	41	Hall
15	Mesa II, Mine 1, P-150	42	Nakai Chee Begay
16	Mesa II, Mine 4	43	Jimmie King No. 9
17	Mesa II Pit	44	Tommy James (Fall Down Mesa)
18	Mesa II 1/4	45	Step Mesa
19	Mesa II 1/2	46	Flag No. 1
20	Mesa II 1/2, Mine 4	47	Black No. 1 (Flag No. 2)
21	Mesa III	48	Black No. 2 (West)
22	Mesa III, Northwest	49	Black No. 2 (Bare Rock Mesa)
23	Mesa III, West	50	Knife Edge Mesa
24	Mesa IV, Mine 3	51	Joleo
25	Mesa IV, Mine 2	52	Cisco
26	Mesa IV, Mine 1	53	Camp
27	Mesa IV, West		

See table 3 for the production statistics on these individual mines.

is 10 to 20 inches. The mountains are covered with snow in the winter, but in the broad valleys around the mountains, snow usually melts between storms. Temperatures range from minus 20 degrees to 105 degrees F. The problem of maintaining mine access roads during the winter is important and should be considered in exploration and mining costs.

Juniper and pinyon are abundant at elevations between 6,000 and 7,000 feet. Ponderosa pine and quaking aspen forests cover most of the shady northeastern mountain slopes above the 7,000 foot elevation. The timber is available for use in the mines. Several species of <u>Astragalus</u>, a selenium (and uranium) indicator plant are locally abundant in many mineralized areas.

Three small springs were developed into supplies of water for drilling and mining. One is on Camp Mesa, another between Mesa I and Mesa I 1/2, and a third at the back of Mesa VII. The rate of flow of the springs is on the order of several gallons to several tens of gallons per minute. In addition to these sources, drinking water for the school, trading post, and mine camps is obtained from a shallow well in the wash just west of Cove School.

Land Status

The area is part of the Navajo Indian Reservation and is under the jurisdiction of the Bureau of Indian Affairs, U. S. Department of the Interior and the Navajo Tribal Council. Leases and mining permits are issued to individual Navajos. The lease or permit holder can assign his mining rights to a company or individual, under Tribal regulations. The maximum amount of ground an individual Navajo can hold is 960 acres.

The scale of royalties paid the Navajo Tribe under regulations approved by the Tribal Advisory Committee in January 1957 is as follows:

Mine value per dry ton of ore	Royalty, percent of mine value of ore
$ .01 to $ 7.50	2.5
7.51 to 14.00	5
14.01 to 20.00	10
20.01 to 30.00	12
30.01 to 40.00	13
40.01 to 50.00	14
50.01 to 60.00	15
60.01 to 70.00	16
70.01 to 80.00	17
80.01 to 90.00	18
90.01 to 100.00	19
100.01 or more	20

The scale of royalties paid the Navajo assignor is as follows:

Mine value per dry ton of ore	Royalty, percent of mine value of ore
$30.00 or less	2
30.01 to $60.00	3
60.01 to 80.00	4
80.01 or more	5

The mine value of the ore is the dollar value per dry ton of crude ore as paid by a Government agency or other buyer, less any allowances for transportation or development, and less any treatment cost. When minerals or other products, such as vanadium, are recovered that are not included in determining mine value per dry ton, the Tribe receives an additional royalty of 10 percent of the gross value of such products and the assignor 5 percent.

The Tribe also receives 10 percent and the assignor 5 percent of any bonus paid by the AEC for new discoveries under the Domestic Uranium Program Circular 6.

Mining Methods

Although some shallow or exposed ore bodies have been successfully mined by stripping and open pit methods, more ore bodies were mined by room and pillar methods or modifications of it. Figure 4 illustrates the workings of a typical mine in a large ore body. The larger mines operated the year round on a two or three shift basis. W. L. Dare, of the U. S. Bureau of Mines, has described the operations of Kerr-McGee Oil Industries, Inc. (Dare, 1961), and the mining by Climax Uranium Company at the Frank No. 1 Mine (Dare, 1959).

Previous Work

Strobell (1956) studied the geology of the Carrizo Mountains, and included most of the Lukachukai Mountains in his geologic map of the area. Masters (1953) reported on the initial geologic investigations of the uranium deposits by the AEC. Kosatka (1956) summarized the the AEC drilling projects and related geologic studies. Nestler and Chenoweth (1958) mapped ten mines in the Lukachukais to determine ore controls and guides. Chenoweth and Learned (1970) prepared a map showing the mine locations and their production statistics. Scarborough (1981), in his report on uranium in Arizona, published maps of the workings of the larger mines.

Acknowledgements

This paper is largely the result of geologic studies by the author and the late R. K. Nestler during the late 1950's when ore deposits were studied in detail to determine and evaluate the comparative importance of sedimentary and tectonic ore controls for the AEC. During the 1960's the author continued to monitor the exploration and mining activities in the Lukachukai for the AEC. The cooperation of Kerr-McGee Oil Industries, Climax Uranium, Walter Duncan Mining, Boyd Hall, and the Navajo Tribal Mining Department is greatfully acknowledged.

GENERAL GEOLOGY

The Lukachukai Mountains lie on the northeast flank of the Defiance Uplift which separates the San Juan Basin on the east, from

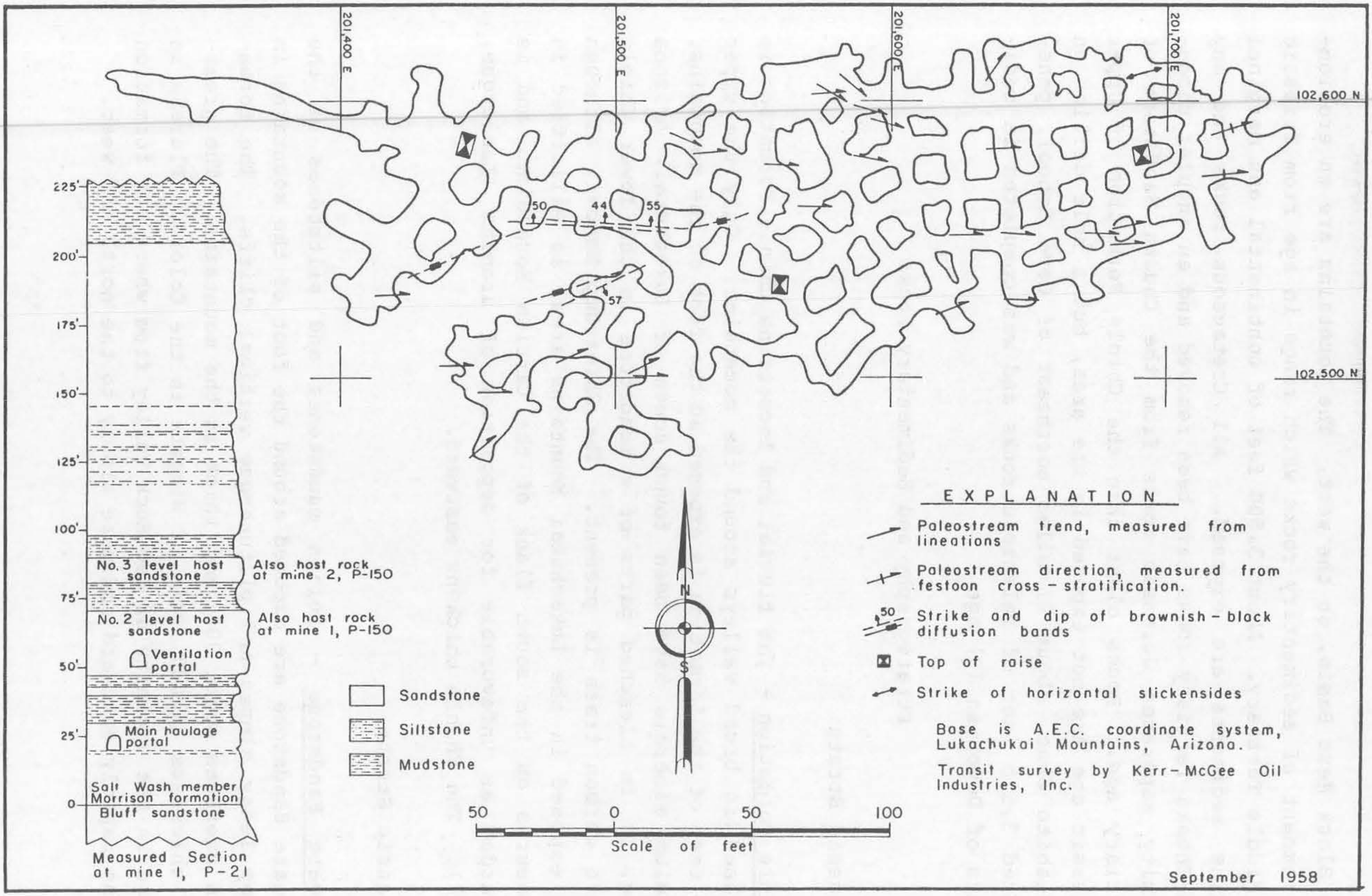


Figure 4. Mesa II Mine 1, P-21, No. 3 level, Apache County, Arizona (after Nestler and Chenoweth, 1958)

the Black Mesa Basin, on the west, The mountains are an erosional remnant of sedimentary rocks which range in age from Triassic to Middle Tertiary. About 3,500 feet of continental and marginal marine sediments are exposed. All Cretaceous rocks and any pre-Chuska Tertiary rocks have been removed and an angular unconformity separates Jurassic rocks from the Chuska Sandstone of Tertiary age. Rocks older than the Chinle Formation of Upper Triassic age are not exposed in the area, but a hole drilled on Beclabito dome, about 21 miles northeast of Cove School, penetrated 3,515 feet of Paleozoic rocks and was completed in sediments of Devonian (?) age.

Stratigraphy and Sedimentary Rocks

Triassic Strata

Chinle Formation - The fluvial and lacustrine Chinle Formation is exposed in broad valleys around the mountains. Only the upper 700 feet of the formation is exposed at the foot of the mountains. Uranium minerals have been found south of Lukachukai, Arizona (fig. 1) in bleached parts of a sandstone in the lower Chinle where carbon trash is present. The Shinarump Member, although not exposed in the Lukachukai Mountains area, is silicified in exposures on the south flank of the Carrizo Mountains, and is regarded as unfavorable for deposition of uranium (Labrecque, 1957). The Chinle thickens eastward.

Jurassic Strata

Wingate Sandstone - Eolian sandstones and siltstones of the Wingate Sandstone are exposed around the foot of the mountains in steep ledgy slopes and picturesque vertical cliffs. The formation averages about 800 feet thick in the mountains. The greatest thickness (1,000 feet) of Wingate in the Colorado Plateau is found in the vicinity of Red Rock Valley from where the formation thins rapidly eastward and more slowly to the north and west.

Kayenta Formation - The fluvial Kayenta Formation thins to a wedge edge on the west side of Mexican Cry Mesa. It is 23 feet thick on Cove Mesa to the north of the mountains. The formation thickens to the west and north and is absent east of the Carrizo Mountains.

Navajo Sandstone - The eolian Navajo Sandstone, which is nearly co-extensive with the Kayenta Formation, is exposed as a wedge edge on a bench northwest of Mexican Cry Mesa. It is 3 feet thick on Cove Mesa. The sandstone thickens to the northwest.

Carmel Formation - The Carmel Formation consists of marginal marine siltstones and mudstones which thin southeastward and pinch out in the Lukachukai Mountains area. It overlaps the Kayenta and Navajo feather edges and rests unconformably on the Wingate Sandstone. The formation is 23 feet thick on Mexican Cry Mesa and becomes a wedge edge on Mesa V and between Step and Flag Mesas. Thinning may be due to pre-Entrada erosion or by lateral gradation into the silty facies of the Entrada Sandstone, or both (Strobell, 1956).

Entrada Sandstone - The marginal marine sandstones and siltstones of the Entrada are partly sub-aerial and partly sub-aqueous (Strobell, 1956). The formation is exposed around the perimeter of the mountains and rests conformably on the Carmel where present; where the Carmel is absent, the Entrada rests unconformably on the Wingate Sandstone. In the Lukachukai Mountains the Entrada Sandstone averages 100 feet in thickness.

Todilto Limestone - The Todilto Limestone is absent; its nearest expsoure is on the east flank of the Carrizo Mountains, where it is 2 feet thick.

Summerville Formation - The marginal marine interbedded sandstones and siltstones of the Summerville Formation overlie the Entrada Sandstone and are exposed around the perimeter of the mountains. The typical red and white banding described in other localities is usually absent in the Lukachukai Mountains. The

Summerville grades into and intertongues with the overlying Bluff Sandstone. In the Lukachukai Mountains the formation averages about 90 feet in thickness.

Bluff Sandstone - The Bluff Sandstone is of eolian origin and is exposed around the perimeter of the mountains. It locally grades into or intertongues with the overlying Salt Wash Member of the Morrison Formation, but the contact is usually easy to distinguish. The Bluff averages about 50 feet in thickness in the Lukachukais. The USGS now considers the Bluff to be a member of the Morrison Formation (Peterson and Turner-Peterson, 1987).

Morrison Formation

Salt Wash Member - The Salt Wash Member of the Morrison Formation is the only commercial ore bearing unit. It crops out continuously around the perimeter of the mountains, as far southeast as Mesa I and Two Prong Mesa, but beyond this it has been removed by pre-Chuska erosion. In all, only 12.5 square miles of the mountains are underlain by this member of the Morrison (fig. 3). Festoon cross-stratification, current lineation, rib-and-furrow, and ripple marks are common sedimentary structures in the sandstone units. Their azimuths provide data on paleostream direction. Sand-filled mud cracks and pre-consolidation slump structures are also common. Cross-stratified sandstones are interbedded with siltstone and claystone. The sandstone commonly contains mud galls and claystone splits; mudstone pebble conglomerate or edgewise conglomerate lenses or splits often separate individual sandstone lenses within a sandstone unit. Carbonized plant material, ranging in size from small flecks to logs, is widely distributed and locally abundant. The base of the Salt Wash is marked by the lowest cut-and-fill type bedding, and over most of the area by six inches to two feet of white calcareous sandstone which is the uppermost part of the Bluff Sandstone (Masters, 1953). Sandstones of the Bluff are medium-grained, well rounded and frosted; basal Salt Wash sandstones are fine- or very fine-grained, usually subangular and are not frosted.

The contact is generally easy to distinguish, but on the west side of Mesa II the contact is gradational through a vertical zone of five feet in which Bluff- and Salt Wash-type lithologies are present. The upper part of the Salt Wash intertongues with the overlying Recapture Member, and the lithologies are so similar as to make distinction between the two members nearly impossible without microscopic examination. On gamma-logs, a characteristic two-pointed deflection marks a gray lacustrine mudstone bed near the contact with the Recapture Member, and this bed is arbitrarily picked as the top of the Salt Wash. Laboratory examination reveals that this anomalous radioactivity is caused by mixture of very fine, granular secondary hydrated uranium carbonates or oxides (Laverty, 1953).

The Salt Wash was deposited by aggrading streams in a large and complex alluvial system whose source was in the Sevier Highlands, west of the Colorado Plateau (Peterson and Turner-Peterson, 1987). It was derived mainly from older sedimentary formations, and only minor contributions came from igneous and metamorphic rocks. Fresh angular feldspar and quartz grains in outcrops of the Four Corners region suggest that some material was brought from the Recapture source by north-flowing streams cutting into and through sediments deposited by east- or southeast-flowing streams. The thickness of the Salt Wash ranges from about 100 feet on Mesa I to 180 feet on Thirsty Mesa. The Recapture member is thinnest in areas where the Salt Wash is thickest.

The Salt Wash alluvial complex divides into two tongues at the south end of the ancestral Monument uplift. The southern or small tongue extends into northeastern Arizona, and the northern or larger tongue extends into southeastern Utah and southwestern Colorado. The Lukachukai Mountains are near the thickest part of the southern tongue which pinches out by non-deposition to the southeast near Toadlena, New Mexico and to the north in the Aneth, Utah area.

Masters (1953) postulated that three facies of the Salt Wash, representing different depositional environments, are present across the Lukachukai Mountains. He states that a thick continuous sandstone facies grades southeastward into a lenticular sandstone and mudstone facies, which in turn grades southeastward into a mudstone and stray sandstone facies. He also states that a lenticular sandstone and mudstone facies exactly coincides with the ore trend or belt. Masters suggests that the facies relationsips are to be attributed to the loss of velocity in Salt Wash streams and consequent deposition.

Sedimentary trends do not substantiate this conclusion which would require deposition by predominantly east to southeast-flowing streams over the whole area. Moreover, Nestler and Chenoweth (1958) show that thick, continuous sandstones comprising up to 90 percent of the Salt Wash are present in Masters' lenticular sandstone and mudstone facies near the change to mudstone and stray sandstone. This evidence suggests that the boundaries of facies changes, as outlined by Masters are over simplified and that they do not exert the control over configuration of the ore belt as originally believed.

Recapture Member - The fluvial interbedded sandstones and mudstones of the Recapture Member crop out on the higher parts of the mesas, but are usually rather poorly exposed. The major source of Recpature sediments (Craig, et al., 1955) was probably in west central New Mexico in an area of pre-existing igneous, metamorphic, and sedimentary rocks. The member was deposited by streams in an alluvial fan environment similar to that of the Salt Wash. The Salt Wash and Recapture fans coalesced in a wide belt near the Four Corners region. Probably the anomalous north and north-east trending stream patterns in the Salt Wash sandstones and the similar lithology of Recapture and Salt Wash sandstones of the Lukachukai Mountains are a result of the influence of Recapture streams and clastics on Salt Wash deposition. In the Lukachukai Mountains, the Recapture Member ranges from 250 to 400 feet in thickness. Sub-ore-grade uranium deposits are found in the Recapture on Mesa I, Flag, Step and Three Point Mesas. Ore-grade uranium deposits occur in the upper Recapture near Sanostee, New Mexico, about 22 miles southeast of Cove School (fig. 1).

Westwater Canyon Member - The Westwater Canyon Member consists of fluvial sandstone and minor amounts of mudstone. Locally pre-Chuska erosion has removed the member from the southern part of the area. Facies distribution of the member (Craig, et al., 1955) indicates a major source in west-central New Mexico in an area of igneous, metamorphic, and sedimentary rocks. The member was formed as a broad, fan-shaped alluvial plain similar to that of the Recapture. The member is 280 feet thick on Mexican Cry Mesa and is missing south of Mesa II and north of Flag Mesa. The Westwater Canyon Member is an important host rock for the uranium deposits in the Ambrosia Lake, New Mexico area, but is barren in the Lukachukai Mountains. A comparison of the lithologies from the two areas is as follows. (1) In the Lukachukai Mountains, the Westwater sandstone contains no humates; at Ambrosia humates are abundant. (2) It is usually pink or red, whereas at Ambrosia Lake the sandstone is light gray over broad areas interrupted by areas of pink to tan coloration. (3) Westwater sandstone in the Lukachukais contains less feldspar and less interstitial mud than the same unit at Ambrosia Lake.

Brushy Basin Member - The lacustrine Brushy Basin Member has been locally removed from the Lukachukai Mountains area by pre-Chuska erosion, but it is exposed east of the area around the flanks of Beautiful Mountain (fig. 1).

Cretaceous Strata

Pre-Chuska erosion has locally removed all Cretaceous rocks which may have been deposited in the Lukachukai Mountains area. Dakota Sandstone, Mancos Shale, and Gallup Sandstone are exposed just east of the area around the flanks of Beautiful Mountain.

Tertiary Strata

Chuska Sandstone - The eolian Chuska Sandstone is exposed on the upper slopes of the mountains. A resistant silicified unit of the Chuska caps the main mountain ridge. The Chuska unconformably overlies the folded and truncated Triassic and Jurassic rocks so that from northwest to southeast it rests on successively older beds. Approximately 700 feet of Chuska Sandstone occurs in the Lukachukais. The Chuska is considered to be Oligocene and Miocene (?) in age.

Igneous Rocks

A small dike which intrudes the Salt Wash on Mesa I is the only exposed igneous rock in the Lukachukai Mountains area. The rock is a member of the minette-vogesite group (S.R. Austin, written communication, 1957). The dike contains numerous xenoliths, one of which was identified as quartzite, formed by contact metamorphism of argillaceous sandstone. Sills, dikes, plugs, volcanic flows, and a laccolith are present in the surrounding area. The laccolith, sills, and dikes of the Carrizo Mountains are diorite porphyry; the dikes and plugs in Red Rock Valley and in the Chuska Mountains are monchiquite (Williams, 1936) and are associated with tuff-breccia containing xenoliths of the underlying sedimentary and crystalline rocks. Extrusive rocks of the Chuska Mountains are sanidine basalt (Williams, 1936).

There is no evidence to suggest a direct time or space relationship between the igneous rocks and the formation of ore bodies, either in the Lukachukai Mountains or in surrounding areas. However, at the Zona No. 1 Mine in the north Carrizo Mountains, between Beclabito and Teec Nos Pos (fig. 1), post-ore silicification and metamorphism suggest that the uranium-vanadium mineralization occurred before the intrusion of the 68 Ma Carrizo laccolith (Armstrong, 1969). Similar age relationships have been described by Corey (1958) at the Nelson Point No. 1 Mine in the east Carrizo Mountains, north of Red Rock Trading Post.

Structure

Regional

The Lukachukai Mountains are on the northeast flank of the Defiance Uplift, a north-trending structure 110 miles long and 50 miles wide (fig 4). To the west, the rocks dip gently toward Black Mesa basin which is separated from the Defiance uplift by

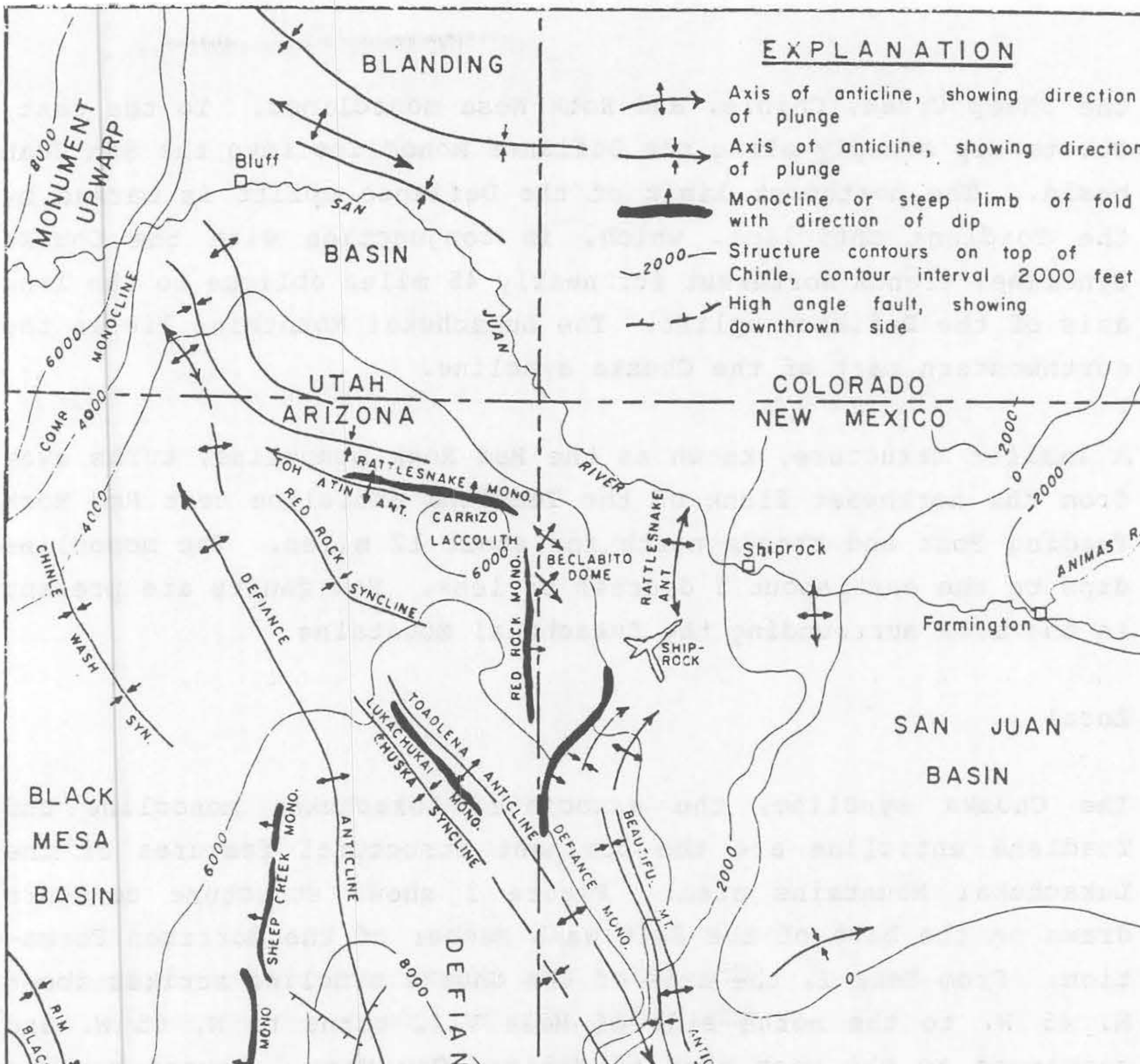


Figure 5. Tectonic Map, Four Corners Region

the Sheep Creek, Chinle, and Rock Mesa monoclines. To the east, strata dip steeply along the Defiance monocline into the San Juan basin. The northeast limit of the Defiance uplift is marked by the Toadlena anticline, which, in conjunction with the Chuska syncline, trends northwest for nearly 45 miles oblique to the long axis of the Defiance uplift. The Lukachukai Mountains lie in the northwestern part of the Chuska syncline.

A smaller structure, known as the Red Rock monocline, turns away from the northeast flank of the Toadlena anticline near Red Rock Trading Post and trends north for about 12 miles. The monocline dips to the east about 5 degrees or less. Few faults are present in the area surrounding the Lukachukai Mountains.

Local

The Chuska syncline, the associated Lukachukai monocline and Toadlena anticline are the dominant structural features of the Lukachukai Mountains area. Figure 2 shows structure contours drawn on the base of the Salt Wash Member of the Morrison Formation. From Mesa I, the axis of the Chuska syncline strikes about N. 45 W. to the north side of Mesa VII, turns to N. 65 W. and continues to the west edge of Mexican Cry Mesa. Beyond Mexican Cry, the axial line swings westward, then northward for several miles before the fold dies out. The axis plunges to the northwest but not at a constant rate. From Mesa I to the southeast side of Mesa VI, the plunge is about one half degree; from Mesa VI to the east side of Mexican Cry Mesa the plunge is only 0.1 degree; across Mexican Cry Mesa the plunge is again about one half degree. The Chuska syncline is sharply asymmetric. The steeply dipping limb of the syncline, here termed the Lukachukai monocline, faces southwest opposing the regional dip off the Defiance uplift. The axis of the Toadlena anticline nearly parallels that of the syncline and plunges northwest at a variable rate. Although the Lukachukai monocline may be the surface expression of a deep-seated fault, no faults as such are known in the area.

After studying the sedimentary trends in the Salt Wash, Stokes (1954) suggested the possibility that the Lukachukai monocline was slightly active in Jurassic time and may have influenced the stream directions. Changes in stream directions could account for the deposition and burial of the detrital organic material in the sediments.

Nestler and Chenoweth (1958) measured the joints throughout the Lukachukai Mountains. Although the joints which were measured do not form a well-defined pattern, they may be divided into three major sets and one minor east-west set. Of the major sets, one is nearly parallel to the axis of the syncline, another is nearly perpendicular to the axis. These two sets may be classed as a tension system of longitudinal and cross joints, possibly related in origin to the plunging syncline, and are distributed widely over the entire area. The strike of the longitudinal and cross joints changes across the mesas to that they are always nearly parallel and nearly perpendicular to the curving axis of the syncline until, on Mexican Cry Mesa, the longitudinal and cross curving joints are nearly north-south and east-west.

The other major set of joints strike N 5 E to N 25 E and form a 45 to 60 degree angle with the axis of the syncline. These obliquely striking joints were found only on the area corresponding to the ore belt. Similar joints were found in the northwestern tip of Mexican Cry Mesa but these strike N 40-60 E.

The east-west striking joint set appears to be a minor set, but it also was found in the area of the ore belt. Since the only area of any extent which contains the N 5 E to N 25 E joint set is the ore belt, the inference may be drawn that the location of th ore belt is genetically related to the joints. Furthermore, in the vicinity of ore deposits north of the Lukachukais, on East and West Mesas, on Cove Mesa, and in other ore-bearing areas around the Carrizo Mountains, joints striking N to N 25 E - such as those present in the ore belt of the Lukachukai Mountains-are a prominent set. Similar sets were not found at any of the barren localities around the Carrizo Mountains where joints were measured, (R.E. Hershey, personal communication, 1958).

URANIUM-VANADIUM DEPOSITS

Host Rocks

Ore bodies in the Lukachukai Mountains are in the Salt Wash Member of the Morrison Formation, but sub-ore-grade deposits have been found in the overlying Recapture Member and in the Chinle Formation. The stratigraphic position of host units within the Salt Wash ranges from 35 to 80 feet above the Salt Wash-Bluff contact and although the top of the Salt Wash is very poorly defined, all of the ore deposits are in, roughly, the two middle quarters of the Salt Wash. Neither ore nor protore is known in the lower 20 feet of the Salt Wash, but protore may occur at any other stratigraphic position within the member. Figure 4 illustrates the relationships of the various ore-bearing sandstones on the south end of Mesa II.

Lithology

The host sandstone units, ranging from 10 to 40 feet in thickness, are white, gray, limonitic brown, or red and contain mud galls, claystone splits, and mudstone pebble conglomerate lenses. The host sandstone changes from its normal color of pink or reddish-brown to gray or tan in the vicinity of ore bodies, which usually contain red, brown, and black stains. The sandstones are fine-grained, lenticular, and cross-stratified; carbon is locally abundant, particularly in sandstones deposited by east-and southeast-flowing streams. Claystone and/or siltstone units, which are laterally continuous across one or two mesas, nearly always underlie and frequently overlie the host units. The vertical interval of the host unit through which ore is distributed seldom extends through the total thickness of the host unit; instead, barren rock nearly always separates the ore from the bottom and frequently from the top of the host unit.

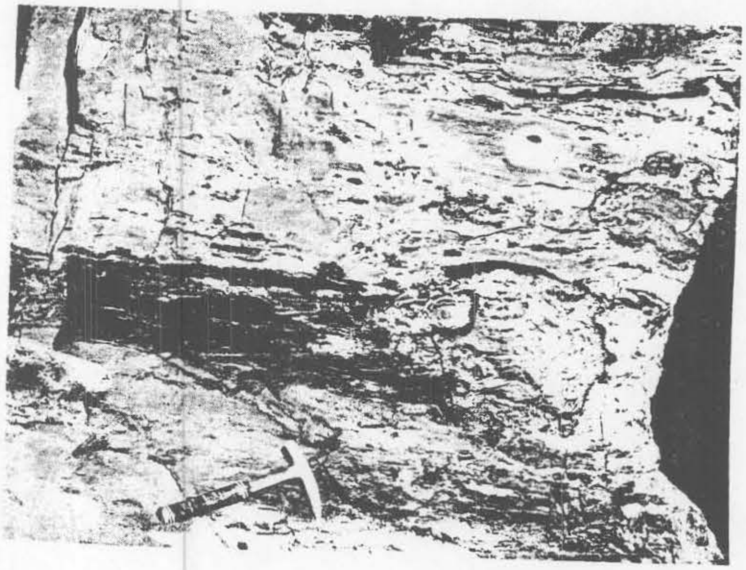
The most common occurrences of uraniferous material are: 1) in cross-stratified sandstone containing red, brown, and black stains and cements which give the ore a characteristic mottled or banded appearance, 2) in limonite-stained, cross-stratified sandstone associated with halos and bands of limonite, 3) in and around carbonaceous plant material, 4) in mudstone pebble conglomerates or associated with claystone splits and partings, and 5) as joint fillings. Sandstones containing some interstitial clay, or having irregular bedding seem to be preferred loci for the deposition of ore. Calcium carbonate concretions and bands, most of which are stained dark gray or reddish-black, are commonly associated with ore, but similar bands and concretions, though most are unstained, are common in barren rock. Figure 6 illustrates some typical ore occurrences.

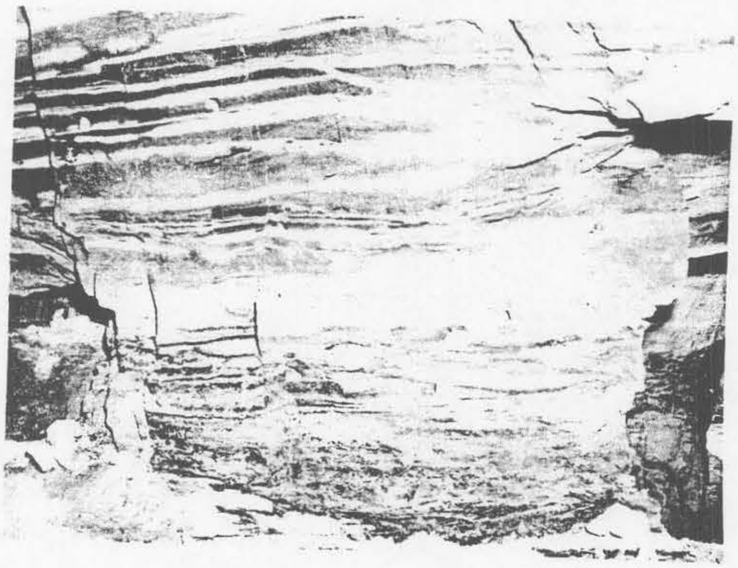
Ore Geometry

The uranium deposits consist of one or more individual masses of ore surrounded or separated by protore. The term ore body, as here applied, refers to the composite extent of both ore and the surrounding protore. The individual masses of ore are here called ore shoots, and such shoots may range up to 350 feet in length. In exceptionally large and rich deposits, the aggregate length of the ore shoots may exceed 1,000 feet.

Nearly all ore bodies are elongate at least three times the width, and most of the ore shoots within the ore bodies are elongate at least twice the width. The overall elongation of every ore body is parallel to paleostream depositional trends measured in and near the ore bodies. More specifically, although the ore body may extend across several separate sand lenses presumed to be deposits in paleostream channels most of the ore shoots lie within and are elongate parallel to sand lenses. All of the ore bodies are lenticular in cross section. Thickness of the ore bodies ranges from one foot to 22 feet.

One of the most striking cluster of ore bodies in the mountains is the trend from Mesa III Mine through the Mesa II 1/2 Mine to the north ore bodies (level No. 2) of the Mesa II P-21 Mine. Striking S.65°E. and extending for 4,200 feet with an average width of 200 to 400 feet, this channel was the source of





Upper and middle photos - Camp Mine

Lower photo - Mesa III Mine

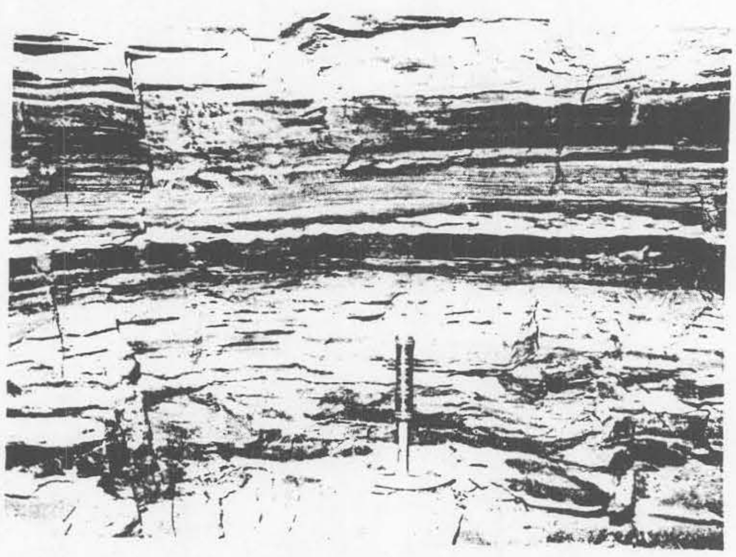


Figure 6. Typical ore occurrence, Camp and Mesa III Mines

approximately 180,000 tons of ore averaging 0.24 percent U_3O_8 and 1.08 percent V_2O_5. Ore bodies in this cluster occurred in a 25 to 30 foot thick sandstone lens, the base of which is approximately 50 feet above the Salt Wash-Bluff contact (fig. 4). Overlying the lower sandstone is another ore-bearing sand lens which trends nearly east-west in the No. 3 level of the Mesa II, P-21 Mine (fig. 4). The combination of these two overlapping, ore-bearing sandstones made the Mesa II, P-21 No. 1 Mine a very productive operation.

Ore Distribution

All the large ore bodies and nearly all of the smaller ones are in a belt which trends slightly east of north, oblique to the axis of the Chuska syncline (fig. 2). Within this belt, ore bodies are found in clusters, and the larger clusters are located either in reentrants at the heads of canyons or near the back end of the mesas. This distribution is probably the result of several factors. Deposits on the narrow, finger-like mesas are most subject to oxidation and probably have been leached. This belt accounts for 99.6 percent of the total production and includes an area of 6.5 square miles.

Drilling depths to the host unit are much greater toward the core of the mountains, and much of this area has been inadequately tested. Perhaps the apparent clustering of ore bodies near the rims in merely a result of greater drilling in these areas where drilling depths are shallow.

All ore bodies are on the southwest limb of the Chuska syncline with the exception of several large deposits on Mesa I and a small deposit on the northern tip of Mesa V which are located on the northeastern limb of the syncline. Within the ore belt only a very small amount of Salt Wash is preserved on the northeastern limb of the syncline. Thus the two occurrences strongly suggest that ore bodies at one time were present on the northeast limb but have since been removed by erosion. No direct relation is apparent between the fold and the location of ore bodies, ore clusters, or the ore belt. As previously noted, all ore bodies are elongate parallel to paleostream depositional trends, but this is not true of all ore shoots. In many times, projections of ore which deviate from the paleostream depositional trend are elongate parallel to prominent joint sets in the mines. Similarly, ore grade and thickness contours, the overall pattern of which closely follow sedimentary trends, show lobes and projections which parallel the prominent joint set (Nestler and Chenoweth, 1958). The largest ore shoot in the Hall Mine on Thirsty Mesa is roughly L-shaped, one branch being parallel to the sedimentary trend, the other parallel to the dominant joints. Thus, joint patterns bear a close relationship to the distribution of ore shoots within an ore body, this relationship appears to be the result of secondary redistribution. No faults are present in the vicinity of the mines that were studied.

Mineralogy

In any of the partly or completely oxidized occurrences, tyuyamunite, the uranium vanadate, is by far the most common ore mineral. It may be irregularly disseminated, concentrated in lenses, or distributed in bands. It may fill the sane interstices, or only coat sand grains, or it may replace calcite and carbon. Other vanadium minerals which have been identified include corvusite, pascoite, hewettite, metarossite, vanadium clays, and possibly montroseite (S.R. Austin, personal communication in Nestler and Chenoweth, 1958). Gruner et al. (1954) reported metatyuyamunite, and the vanadium minerals jascoite, melanovanadite, hummerite, rossite, and metarossite from the mines on Mesa I. Gruner and Smith (1955) identified uraninite in samples from the Camp Mine. Uraninite also has been identified as a replacement in carbonized wood in the Cisco Mine, and as a cement in some ore bodies that are not completely oxidized (Laverty and Gross, 1956).

Ore Guides

All the mines that were studied, the host unit in the vicinity of the ore bodies is predominantly a reduced gray, white, or limonitic-brown. At or near the edges of the ore bodies, these colors either abruptly abut or grade into the red color of the surrounding oxidized country rock. Data concerning whether the color change is a result of the passage of ore solutions is contradictory; however, because of the gray color in down dip oil tests in the San Juan Basin the author believes that at least some, if not most, of the red coloration is a result of oxidation of originally gray sandstone, and that not all favorably colored areas resulted from the passage of ore solutions which altered orginally red rocks to gray.

The ore bodies in all of the mines mapped are elongate parallel to paleostream depositional trends, and although the ore body may extend over several small channels, most of the ore shoots are elongate parallel to and lie within sand-filled channels on the order of 25 to 150 feet wide. The lateral extent of most ore shoots is controlled by the extent of the small channel in which the ore shoots lie, but some ore shoots and extensions are controlled by joints.

The upper limits of ore shoots and ore bodies is often controlled by an overlying claystone, but control of the lower limits is not. Paleostream sedimentary channels, festoons, lineation, and rib-and-furrow trends measured in the mines did not always agree with channel trends outlined on mudstone: sandstone ratio maps of the same area. Over a limited area of one or two mesas, ore is confined to one or possibly two mappable, lenticular units which thicken and thin perceptibly. The ore bodies occur in units showing most rapid variation in thickness. Ore often occurs in muddy sandstones in preference to cleaner sandstones above or below.

Carbon is widely distributed and locally abundant. Some ore is closely associated with carbon trash and logs, but as is common in oxidized deposits, the biggest part of the ore is not closely associated with carbon. In the Lukachukai Mountains carbon in the form of logs and branches is most abundant in sandstones deposited by east and southeast-flowing streams.

Source of the Uranium and Vanadium

The source of uranium in the Salt Wash deposits of the Colorado Plateau is presumed, by most investigators, to have been within the tuffaceous material of the Salt Wash and/or the overlying Brushy Basin siltstones and mudstones. Such a source for the uranium has been proposed for all the principal sandstone uranium deposits in the United States, and in all cases, including the Salt Wash, it is still based more on the presence of such volcaniclastic sediments in each of these districts than on any convincing documentation. Although these relations provide a strong circumstantial argument that these sediments were the source of the uranium, chemical studies are required to test this hypothesis.

Most uranium districts have been shown to occur within regions that contain possible source rocks with anomalous concentrations of uranium. These concentrations may occur as high backgrund values in granites, volcanic sequences, or metasediments. Both uraniferous granites and volcanic rocks are present in the vicinity of the Wyoming basins and the Grants, New Mexico region, and the ore-bearing sands of the Texas deposits are almost always in juxtaposition to the locally uraniferous Catahoula Formation. Similarly, the Colorado Plateau, including the areas of Salt Wash mineralization, is interpreted to be within a province of uraniferous Precambrian basement (Silver et al., 1980). The importance of a uraniferous province to the formation of uranium deposits seems reasonable. It is uncertain, however, whether normal concentrations of uranium in source rocks are adequate to form the deposits, or whether the source rocks need contain truly anomalous uranium concentrations.

The Salt Wash deposits are essentially vanadium deposits, but as yet no convincing case has been made for the source of that vanadium. Favorite hypotheses suggest that it was (a) derived from altered ilmenite and magnetite, (b) introduced diagenetically from the overlying Cretaceous sediments, or (c) was derived from the leaching and erosion of Paleozoic sediments well to the west of the Colorado Plateau. All of these hypotheses are, to some extent, plausible, but are as yet unsubstantiated.

Summary

All of the known large uranium deposits and most of the smaller deposits in the Lukachukai district are located within a rather well-defined belt which trends nearly north-south across the southeastern end of the Lukachukai Mountains, (fig. 3). The ore bodies are elongate and horizontally lenticular in shape and consist of one or more ore shoots surrounded or separated by protore. The composite length of ore bodies consisting of two or more ore shoots separated by protore ranges up to 1,100 feet; indivdual ore shoots range up to 350 feet in length. The length is usually at least three times the width and is parallel to paleostream depositional trends measured in and near the ore bodies. Claystone and/ore siltstone units nearly always underlie and frequently overlie the host sandstone units.

Ore occurs most frequently in trough-type, cross stratified sandstone which fills scours and channels in the underlying claystone units. Lithofacies maps and mine mapping show that ore bodies are restricted to areas of rapid lateral color change which in general are also areas of rapid change in the ratio of mudstone to sandstone. Location of the ore belt is coincident with a set of N. 5 E. to N. 25 E. striking joints, but is controlled by a favorable facies of the Salt Wash sandstone.

AEC DRILLING PROJECTS

Introduction

During the period September, 1950 through August, 1955, the AEC conducted six drilling projects in the Lukachukai Mountains.

Since these projects were higly successful and greatly aided the mining companies in developing minable ore reserves, they are briefly summarized here. Full details are given in the report by Kosatka (1956). Table 2 summarizes drilling statistics for the six projects.

The host target in all holes was the Salt Wash Member of the Morrison Formation. Some holes were drilled into the Bluff Sandstone in order to provide data for drawing a structure contour map, but most holes were bottomed near the base of the Salt Wash. Overlying formations which were penetrated in various holes include the Recapture and Westwater Canyon Members of the Morrison Formation and the Chuska Sandstone. Except for a small amount of coring in the Recapture Member, only the Salt Wash was cored; average core recovery was about 83 percent. Drilling depths ranged from 50 to 950 feet and averaged 204 feet. The maximum depth to the base of the Salt Wash in the mountains would be slightly over 1,400 feet.

Drill holes were located according to various grid patterns or as fences across previously mapped and projected sedimentary channel trends in the Salt Wash. CP-8 drill rigs mounted on two-ton trucks were used for shallower coring. CP-15 and Sullivan HD22 truck-mounted rigs were used for deeper drilling. A Mayhew 1000 truck-mounted rig was used exclusively for plug bit drilling in formations overlying the Salt Wash. Feet drilled per shift ranged from about 50 to 100. Water was hauled from any of the three developed springs.

The drill hole locations were located by closed traverse and transit and stadia survey. Elevations were determined by running closed differential levels, using a transit as the levelling instrument. Coordinates of drill holes were computed to the nearest foot, and elevations were computed to the nearest tenth of a foot.

The drilling program originally consisted of three phases: (1) wide spaced grid pattern, 400- to 800- foot spacing between holes, (2) closed grid pattern, on 100- to 200- foot spacing

Table 2

Summary of drilling statistics, AEC projects Lukachukai Mountains, Arizona

Project Name Contract No.	Contractor	Duration	Total Feet Drilled	Number of Holes	Avg. Depth, Feet	Avg. Spacing Feet	No. of Ore Holes*	No. of Min. Holes	Percent Core Recovery
Lukachukai #1 AT (30-1)-1021	Minerals Engineering Co.	Sep., 1950-Feb., 1951	49,984	322	155.2	213.8	22	88	68.5
Lukachukai #2 AT (30-1)-1139	Minerals Engineering Co.	5-11-51 to 11-21-51	89,887	560	160.5	212.0	75	160	88.0
Lukachukai #3 AT (30-1)-1263	Joy Manufacturing Co.	6-15-52 to 11-21-51	90,000	544	165.4	262.0	98	155	84.6
Lukachukai #4 AT (30-1)-1364	Minerals Engineering Co.	10-20-52 to 4-15-53	12,426	44	282.4	297.0	8	6	85.7
Lukachukai #5 AT (05-1)-234	Minerals Engineering Co.	7-15-53 to 4-30-54	71,683	241	297.4	389.6	25	33	82.6
Lukachukai #6 AT (05-1)-257	Pennsylvania Drilling Co.	7-8-54 to 8-24-55	60,218	124	485.6	487.7	14	27	84.7
	Totals		374,198	1835	203.9		242	469	

*An ore hole is defined as containing at least greater than 1 foot of 0.20% U_3O_8 or equivalent.

between holes, an (3) offset drilling 50-foot intervals, including drilling behind outcrops to delimit exposed ore bodies and arund ore holes and ineralized ground to develop ore reserves.

Drilling commenced in selected areas on the rim and was extended, first, to include favorable portions of the rim, and then, to explore deeper ground away from rims. Several deep holes were drilled across the highest part of the mountains to connect and correlate more concentrated drilling areas.

Project Activities

The discovery of uranium deposits in the Lukachukai Mountains was brought to the attention of the AEC by F. A. Sitton in the spring of 1950. After a brief reconnaissance by AEC geologists an initial drilling project was started in September 1950. Since this was a new area of uranium-vanadium deposits in the Salt Wash Member of the Morrison Formation, the Commission was very interested in locating and developing additional ore reserves in the mountains. The Navajo Tribal Council gave full approval to the work as favorable results wuld result in Tribal royalties and employment for Tribal members. The road construction would provide access for wool hauling, timber cutting, and for grazing on the top of the mountains.

The objectives of the drilling projects were as follows:

(1) To find mineable bodies of uranium ore, (2) to develop sufficient reserves of uranium ore in the areas drilled, by direct delimitation of ore bodies with drill holes, to warrant construction of a 100 ton capacity mill at Shiprock, New Mexico, (3) to discover and develop criteria indicative of ore, ore trends and favorable areas, which would result in geologic information that culd be used to evaluate the ore potential of the Lukachukai Mountains and would aid future private exploration and mining in this and adjoinig areas.

In the original drilling proposal, it was recommended that the major exploratory effort be expended on Mesa I, the discovery area, because of its apparent economic potential and accessibility, although mineralized outcrops were known to exist on other mesas. After drilling started in September 1950, and access roads were completed to Mesas II, III, and IV, the drilling plan was altered to include the exploration of these additional areas. Under the revised program, which provided no increase in total footage, overall hole density was accordingly decreased.

Near the end of the Lukachukai No. 1 project, shallow wagon drilling was tried on Mesa IV but provided unsatisfactory when cuttings could not be blown up to the surface by compressed air due to excessive wetness of the sedimentary rocks.

Further portions of the northeast rims were explored by the Lukachukai No. 2 project. Despite negative drilling recommendations resulting from unfavorable reconnaissance reports, Mesa VII and Mexican Cry were drilled, in addition to Mesas IV 1/2 and V. With closely spaced drill holes, large ore deposits were discovered on the latter two mesas. Mesa V, however, has deposits of marginal grade which have little continuity.

The southeastern rims, from Camp to Flag Mesas were drilled under the Lukachukai No. 3 project. The mesas further to the west, from Flag to Fall Down mesas, were later drilled as part of the Lukachukai No. 6 project.

The Cove Mesa No. 3 contract was amended to allow a portion of the footage under the contract to be transferred to Mesa IV 1/2, where 12,426 feet were drilled under the Lukachukai No. 4 project. As a result of the Lukachukai No. 4 drilling and later reconnaissance, a broad zone of bleached grey sandstone forming an arcuate band across the northeast mesas from Mesa IV 1/2 to Mesa I was discovered. This zone was explored by the Lukachukai No. 5 project.

The final drilling project (Lukachukai No. 6) investigated higher ground adjacent to areas found to be favorable by previous projects. It was the only contract, as originally proposed, for which little or no rim information was available, since deeper ground away from rims was being investigated. Drilling was guided solely by projection of rim and favorability trends from known ground into unexplored ground.

On the first two projects, emphasis was placed on the element of time in the search for uranium, and a hit or miss system of drilling was used to locate ore deposits as rapidly as possible, with a minimum of geologic information collected. A need for more accurate drilling guides, resulted in the start of subsurface studies during the latter part of the second project. Particular attention was paid during the second project to such features as color of sandstone or mudstone, thichness of the unit, presence of cementing material, grain size, bedding, and presence of carbon, all of which may have had some influence on distribution of ore. During the Lukachukai No. 3 project, subsurface data was used for the first time on a large scale to guide drilling, rather than the systematic geometric grid which had been used to explore unknown areas in earlier projects. The program still consisted of three phases, including offset drilling on 25-and 50-foot centers.

When large reserves of mineable uranium ore were found by drilling under the first three of six projects, construction of a processing mill in Shiprock, New Mexico, was begun. The drilling program was modified to eliminate the offset phase of drilling, and emphasis was shifted to the second major objective of the overall exploration program--discovery and development of ore criteria, ore trends, and favorable ground.

Summary

Diamond core drilling projects of the AEC explored approximately three-fourths of the Lukachukai Mountains. A total of 374,198 feet was drilled in 1,835 holes, of which 242 are in ore and 469 show anomalous radioactivity or contain uranium of sub-ore grade for a discovery rate of two mineralized holes for every five holes drilled (table 2).

The drilling projects discovered sizeable ore deposits on Mesas I, II, III, IV, IV 1/2 and V, and smaller scattered deposits were discovered on the other mesas between Mesa I and Mesa V. Only one small deposit on Mesa VI was found between Mesa V and Mexican Cry Mesa. On the southerwestern rims, minable ore deposits were found on Camp, Cisco, Three Point, Bare Rock, Flag, and Fall Down Mesas.

The AEC drilling projects succeeded in discovering minable ore deposits and potential reserves to warrant construction of a mill at Shiprock and developed ore finding criteria, resulting in information which aided exploration and mining in the Lukachukai Mountains area, thus accomplishing the objectives of the program. Total cost of the six drilling projects was approximately $1,288,000, which included construction of 144 miles of access roads to drill sites.

The construction of these roads (fig. 2) by the AEC greatly aided mining companies in access to their leases and mining permits, as well as to areas they needed to drill for development and/or mine planning.

Table 4, in the appendix lists all of the AEC reports that were written as the result of the exploration in the Lukachukai Mountains. Lithologic logs and drill hole location maps of the AEC drilling projects in the Lukachukai Mountains were placed on open file by the Grand Junction Office of the AEC, but are now on file at the U.S. Geological Survey, Branch of Sedimentary Processes, Denver Federal Center, Denver, Colorado.

PRODUCTION HISTORY

Historical Background

The discovery of radium by Marie and Pierre Curie in 1898 led to the realization that all uranium ores contained this new element. Experiments which showed that radium inhibited the growth of certain cancers so astonished the medical profession that an incentive to mine the carnotite ores of southwestern Colorado was created. Shortly before 1910, metallurgical processes for relatively large-scale recoveries of radium were perfected. These improved processes greatly increased the demands for carnotite and accelerated prospecting, especially in southwestern Colorado. This effort spread throughout the Four Corners area and into the Navajo Indian Reservation of northwestern Arizona.

Carnotite-bearing outcrops in the Salt Wash Member of the Morrison Formation in the eastern and western Carrizo Mountains were located by John F. Wade about 1918. In 1920, Wade and associates obtained two leases from the Department of the Interior to mine carnotite. A shipment of 20 tons of ore was made in December 1920 from the northwestern Carrizo Mountains. This shipment would be the first uranium production from Arizona.

Frank L. Hess of the U.S. Geological Survey examined the newly discovered deposits in the Carrizos during 1921. In his description of these deposits, Hess (1924, p.226) stated "Deposits were reported to have been found in the Lukachukai Mountains, Arizona, south of Carrizo Mountain, but no details are at hand." The Lukachukai deposits were apparently never explored as no leases were issued in that area.

During the early 1940's, the Department of the Interior issued five mining leases to mine the carnotite deposits in the Carrizo Mountains for vanadium, to be used in the manufacture of war armaments. Apparently the two mining companies in the Carrizos, Vanadium Corporation of America, and Curran Brothers and Wade, did not prospect in the Lukachukais, as no leases were applied for.

At about the same time, the Army's Corps of Engineers, as part of the Manhattan Project, began a resource appraisal of the uranium possibilities of the Salt Wash Member on the Colorado Plateau. Their work was carried out by a contractor called Union Mines Development Corporation. All known exposures of the Salt Wash Member were prospected and mapped. Exposures of carnotite-bearing minerals, prospects, and mines were mapped and described. Ore reserves were calculated from samples collected on outcrops and in mines. Areas where reserves could be developed by additional drilling were especially noted. Stratigraphic sections of the Morrison and adjacent formations were measured. All of this work was done under the disguise of looking for vanadium (Chenoweth, 1987).

During the summer and fall of 1943, Party No. 1 under Alfred H. Coleman worked on Cove Mesa, East Mesa, and West Mesa in the southern Carrizo Mountains and on Mexican Cry Mesa on the northwest tip of the Lukachukai Mountains (Figure 3). Bad weather in December ended the field work in the Lukachukai Mountains. Coleman planned no further work in the Lukachukais, as the uranium-vanadium occurrences on Mexican Cry Mesa were small and scattered, and he believed that the pre-Chuska unconformity had cut out the Salt Wash beds to the southeast (J.W. Harshbarger, personal communication, 1983). Had mapping continued the next field season, Union Mines geologists would have no doubt discovered the large outcrops of uranium-vanadium minerals in the central and southeastern part of the mountains. The results of Coleman's reconnaissance are given in a report by Webber (1943).

The Atomic Energy Commission (AEC) was established in 1947 and it's uranium procurement program became public. The mining of carnotite ores on the old vanadium leases in the Carrizo Mountains resumed in late 1948. The mines were operated by the Vanadium

Corp. of America (VCA), and the ore was shipped to their mills at Naturita and Durango, Colorado. Ore-buying schedules, bonuses, and other incentives of the AEC stimulated prospecting throughout the Four Corners area. In northeastern Arizona, Navajo prospectors searched for the bright-colored exposures of uranium bearing sandstone.

Early Activities

Early in 1949, Dan Hayes, a prospector from Monticello, Utah, who could speak Navajo, entered the Lukachukai Mountains. He met with Koley Black and Dan Phillips, local Navajos who knew the mountains. Black and Phillips showed Hayes brightly colored outcrops of uranium and vanadium minerals on Mesa I and adjacent mesas. Hayes interested F. A. Sitton of Dove Creek, Colorado to look at the Lukachukai Mountains. Sitton was very interested in the area and began working with Black and Phillips to acquire leases in the Lukachukais.

On May 12, 1949, both Black and Phillips applied to the Navajo Tribal Council for uranium-vanadium leases in the Lukachukais. Due to the rugged topography of the mountains a detailed engineering survey of the area of the leases was required by the Tribal Council and the Bureau of Indian Affairs. On December 20, 1949, lease I-149-IND-8666 was issued to Dan K. Phillips by the Interior Department. This lease consisted of 528 acres, in three parcels, covering the south part of Mesa II, Mesa II 1/2, Mesa IV, and Mesa V. On the same date, lease I-149-IND-8667 was issued to Koley Black, which included 640 acres in three parcels on Mesa I, northern portion of Mesa II, Knife Edge, Bare Rock, and Flag Mesa. On the day the leases were issued, both Phillips and Black assigned a 75 percent interest in their leases to F. A. Sitton.

In the spring of 1950, Sitton built a road from Cove School up the northeast side of Mesa I to the ore-bearing outcrops. A field camp was established on Mesa I. The initial shipment from Mesa I on the Koley Black lease was made to the VCA mill at Durango, Colorado in June, 1950. This shipment consisted of 799 tons of ore that averaged 0.55 percent U_3O_8 and 1.50 percent V_2O_5. Shipments from Mesa I continued in July, September, and December 1950 with the ore being shipped to the AEC ore-buying station at Monticello, Utah. Here the penalty for the lime ($CaCO_3$) content of the ores, in excess of 6.00 percent $CaCO_3$, was less than at Durango. The initial production came from rim cuts. Later, six large underground mines were developed on Mesa I (fig. 3, nos. 1-6), but the production was not separated since it was all from Koley Black's lease.

Sitton built an access road from Cove School up the east side of Mesa II, to reach mineralized exposures on the Dan Phillips lease. Initial production from that lease was obtained in November 1950 from exposures on the tip of Mesa II (fig 3, no. 17). This shipment consisted of 334 tons of ore averaging 0.22 percent U_3O_8 and 0.61 percent V_2O_5. On November 30, 1950, the 75 percent interest in both leases were reassigned to F. A. Sitton, Inc. In December 1950, using AEC built drill roads for access, Sitton began shipments from exposures on the tip of Mesa IV (fig 3, nos. 25,26). Total production from both leases during 1950 was 2,296 tons of ore averaging 0.31 percent U_3O_8 and 0.92 percent V_2O_5 (Figure 7).

Sitton's mining activities created much interest among the local Navajos, many of whom had worked in the Carrizo Mountains and/or in Monument Valley mining carnotite deposits for vanadium in the 1940's. During the summer of 1950, Frank Nacheenbetah located ore-bearing exposures on Mesa IV 1/2. A mining permit, covering 120 acres on Mesa IV 1/2 was issued to him on September 28, 1950. At about the same time, other Navajos such as David Phillips, Dan Phillips, Henry Phillips, Billy Topaha, Tom Joe and Cato Sells were obtaining unnumbered mining permits covering the

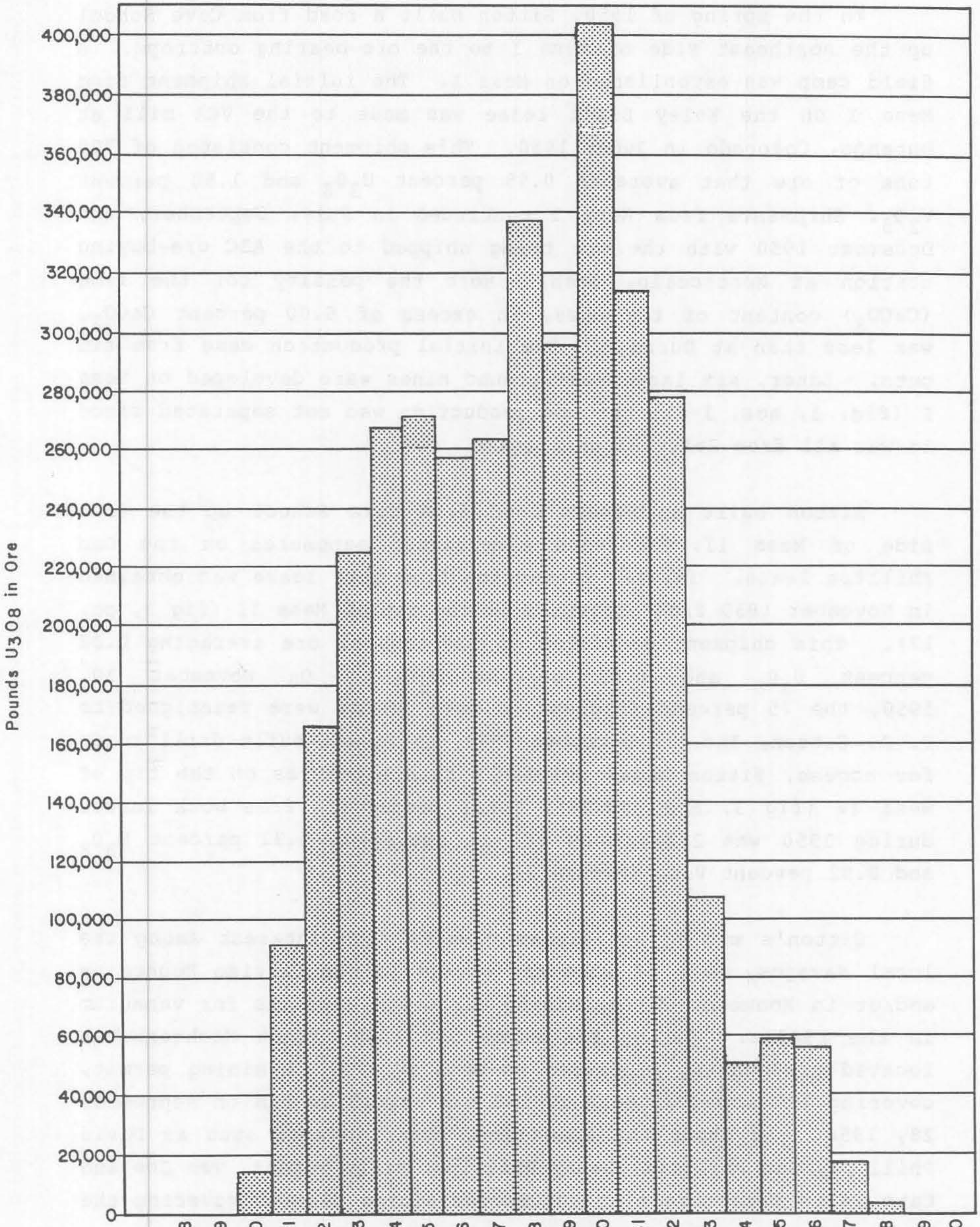


Figure 7. Uranium production Lukachukai Mountains, Apache County, Arizona.

open ground on the northside mesas. Willie Cisco, of Lukachukai, Arizona, located ore-bearing exposures on Camp, Cisco, and Three Point Mesa on the southwest side of the Lukachukai's and claimed them with a mining permit covering 434 acres.

In an agreement dated January 1, 1951, F. A. Sitton, Inc. agreed to pay both Koley Black and Dan Phillips a 5 percent royalty in lieu of the 25 percent interest stated in the original leases. Production by Sitton from the two leases continued on Mesa I, II, and IV during the first half of 1951. When the company ceased production in May 1951, its total production from the Lukachukai Mountains was 8,683 tons of ore averaging 0.25 percent U_3O_8 and 0.84 percent V_2O_5. On March 22, 1951, F. A. Sitton, Inc. applied to the Navajo Tribal Council to lease 160 acres near Shiprock, New Mexico for construction of a 100 ton-per-day mill. On May 3, 1951 the lease was executed by the Tribal Council, but the AEC had not yet approved Sitton's mill proposal.

Early in 1951, Climax Uranium Company of Grand Junction, Colorado signed as operating agreement with Frank Nacheenbetah to develop his Frank No. 1 permit on Mesa IV 1/2. Climax built a road up the north end of Mesa V and across to Mesa IV 1/2. Initial production was obtained in June and consisted of 12 tons averaging 0.43 percent U_3O_8 and 0.85 percent V_2O_5 which was shipped to the AEC buying station at Monticello, Utah. Initial shipments came from expsoure near the east portal (fig 3, no. 30). As mining continued the workings of all three portals (fig. 3, nos. 29, 30, 31) were connected underground. Using the Climax road up Mesa V for access, Cato Sells shipped 54 tons averaging 0.28 percent U_3O_8 and 2.52 percent V_2O_5 from a small open pit on his Cato No. 1 permit on the tip of Mesa V (fig. 3, no. 36). Sells also began an underground operation on the north side of Mesa V (fig. 3, no. 37). All ore from the Cato No. 1 permit was shipped to Monticello.

During the summer of 1951, the Dulaney Mining Company of Cortez, Colorado employed Raymond Starr, a prospector from

Mancos, Colorado, to map and sample all of the known mineralized outcrops in the Salt Wash between Mesa I and Mesa V. Starr's maps indicated an excellent potential to develop additional mines in the Lukachukais.

In August 1951, the newly formed Navajo Uranium Company of Cortez, Colorado, acquired F. A. Sitton, Inc., and the Black and Phillips leases. Richard O. Dulaney Jr. was the president of Navajo Uranium, and other officers were Edward Key and G. R. Kennedy. Navajo Uranium began mining in September 1951, operating the mines on Mesa I and opening up new mines on the south side of Mesa V (fig. 3, nos. 34, 35). Of the 91,009 pounds U_3O_8 produced in 1951 (Figure 7), 60 percent came from the mines on Mesa I.

Using Raymond Starr's information and the encouraging results of the initial AEC drilling, officials of Navajo Uranium proposed to the AEC the construction of a 300 ton-per-day mill in Shiprock, New Mexico to process the Lukachukai ores and other ores in the Four Corners region. The mill proposal was not approved but permission was given to construct an ore-buying station at Shiprock. The station was built by Navajo Uranium and was operated for the AEC by a contractor, American Smelting and Refining, Inc. The station began operating on January 17, 1952 and provided a market for all non-VCA controlled ores in northeastern Arizona and northwestern New Mexico.

Early in 1952, the Navajo Tribe began issuing numbered mining permits (MP). These permits could be assigned to an individual or company to operate a mine on them. The assignment of Willie Cisco's MP-13 to Walter Duncan Mining Co. of Oklahoma City, Oklahoma was approved on June 17, 1952. Duncan began shipments from the Joleo Mine (fig. 3, no. 51) on Three Point Mesa in July. The initial shipment received at Shiprock consisted of 25 tons averaging 0.27 percent U_3O_8 and 0.72 percent V_2O_5. The mine was named for John Masters and Leo

Miller, AEC geologists who located the original ore-bearing outcrop on Three Point Mesa.

During 1952, Frank Nacheenbetah continued shipments from his MP-72 on Mesa IV 1/2, being operated by Climax Uranium, and Cato Sells operated an underground mine on his MP-55 on Mesa V (fig. 3, no. 37). Ore from both operations was shipped to the AEC buying station at Shiprock.

Navajo Uranium continued mining at the mines on Mesas I, IV and V during the early part of 1952. At the same time, Kerr-McGee Oil Industries, Inc. of Okahoma City, Oklahoma became interested in the Navajo Uranium Company's operations in the Lukachukais, and the potential of the area as indicated by Raymond Starr's maps and the drilling being done by the AEC.

The Kerr-McGee Era

In May 1952, Kerr-McGee acquired the Navajo Uranium Company and a 75 percent interest in the Koley Black and Dan Phillips leases. They also acquired the ore-buying station at Shiprock which had been leased to the AEC by Navajo Uranium. When Navajo Uranium was acquired by Kerr-McGee, the firm's total production from the Lukachukais had been 23,957 tons of ore averaging 0.31 percent U_3O_8 and 1.08 percent V_2O_5.

Kerr-McGee signed operating agreements with David, Dan, and Henry Phillips for their unnumbered mining permits on Mesa II, I 3/4, and III respectively. Later in 1952, Kerr-McGee opened up two new mines (fig. 3, nos. 13, 15), each on opposite sides of the canyon separating Mesa II and Mesa I 3/4, both on the Dan Phillips permit. This permit would later be given the number, 150. A new pit on the central part of Mesa II, (fig. 3, no. 16) and a small mine on the southern part of the west side of Mesa II 1/2 (fig. 3, no. 20) were also started.

Total production during 1952 increased to 166,302 pounds U_3O_8 (Figure 7), with 64 percent of the uranium produced by the mines on Mesa I and 16 percent by the Frank No. 1 Mines.

Kerr-McGee's acquisition of the 75 percent interest of the Koley Black and Dan Phillips leases was approved by the Bureau of Indian Affairs on January 26, 1953. Kerr-McGee's operations at Shiprock and in the Lukachukai Mountains were named the Navajo Uranium Division, thus Kerr-McGee became the first major petroleum company to enter the uranium exploration and mining business. Field operations were carried out from the Sitton camp on Mesa I.

Starting in May 1953, Kerr-McGee began a yearly exploration drilling program to locate and delineate new ore deposits. This drilling was done with rotary drills, the type used in seismic survey for petroleum exploration. Holes were probed with gamma-ray detection equipment mounted in a Jeep. This exploration technique was new to the Colorado Plateau where core drilling had been used for the exploration of uranium-vanadium deposits. Approximately 60,000 feet of drilling was done annually by Kerr-McGee during the 1950's. Much of the drilling was in areas where the AEC drilling had located ore grade material in their core holes.

Kerr-McGee continued to mine on Mesas I, I 3/4 (fig. 3, no. 13), II (fig. 3, no. 15), IV (fig. 3, nos. 24, 25, 26) and V, and started a new mine on Flag Mesa during 1953. Production at Frank Nacheenbetah's mines on Mesa IV 1/2 also continued (fig. 3, nos. 29, 30, 31). Cato Sells continued production at Mesa V and started a new mine, Cato No. 2 (fig. 3, no. 39), on the south side of Mesa VI in 1953. Walter Duncan started new mines on both Camp and Cisco Mesas (fig. 3, nos. 52, 53) in 1953 and continued production at the Joleo Mine on Three Point Mesa, all on Willie Cisco's MP-13. Total production from the Lukachukai Mountains increased to 224,666 pounds U_3O_8 during 1953 (Figure 7).

On August 17, 1953, Kerr-McGee Oil Industries, Inc., Navajo Uranium Division signed a contract with the AEC to produce uranium concentrates from a processing mill to be built at Shiprock, New Mexico, near the site of the AEC buying station. Construction began in the fall of 1953 and the mill went on stream in November 1954, with a nominal capacity of 300 tons of ore per day (Albrethsen and McGinley, 1982). On November 1, 1954, Kerr-McGee assumed the operation of the AEC ore buying station. The AEC later sold the ore piles at the buying station to Kerr-McGee. This material amounted to 129,638 tons of ore averaging 0.28 percent U_3O_8 and 1.08 percent V_2O_5 (Albrethsen and McGinley, 1982).

The original uraniun-vanadium mill utilized an "acid cure" process to improve the recovery of vanadium from the relatively low lime, high vanadium ore. There were materials handling problems with the initial mill design so the acid cure was abandoned in favor of conventional agitation leach in 1955. Concurrently, Kerr-McGee added a solvent extraction (SX) circuit to supplement the original fixed-bed ion exchange circuit. The SX circuit operated so well that eventually the operation of the ion exchange unit was discontinued.

The mill used conventional ore crushing, and grinding, followed by a two stage hot sulfuric acid leach with oxidant to solubilize both the uranium and vanadium. After liquid solids separation in classifiers and thickeners, the pregnant solution was treated by separate SX circuits to recover first the uranium, then the vanadium (Albrethsen and McGinley, 1982). Kerr-McGee also built an employee housing complex in Shiprock on land leased from the Tribal Council.

During the years 1954 through 1957, uranium production from the Lukachukai Mountains was fairly stable, ranging from 256,000 to 271,000 pounds of U_3O_8 per year (Figure 7). Principal producers were Kerr-McGee mines on Mesas I 3/4, II, III, IV 1/2 and Flag Mesa, as well as Walter Duncan's Camp Mine and Frank Nacheenbetah's mines on Mesa IV1/2.

During 1954 Kerr-McGee began production from the large deposit they developed on Henry Phillip's MP-93,on Mesa III (fig. 3, no. 21). The Mesa III Mine was planned to utilize a sublevel haulage system in order to eliminate many of the problems encountered in the Mesa I Mines where on level haulage encountered multiple ore horizons. Initial production also commenced at a new mine on Tom Joe's MP-57 on Mesa IV 1/2 (fig. 3, no. 32), just north of the Frank No. 1 Mines. In the summer of 1954, Kerr-McGee moved their field camp from Mesa I to a site near Cove School.

Kerr-McGee briefly reopened the Mesa IV No. 1 Mine (fig. 3. no. 26) during 1955 and closed the Mesa II and Mesa I 3/4 Mines on Dan Phillips' MP-150 which had been operating since 1952. By the fall of 1955, Kerr-McGee controlled 2,965 acres in the Lukachukai Mountains through the assignment of leases and mining permits. Tribal regulations allowed ore processors to hold excess of the usual 960 acres allowed one individual or company.

In 1955, Cuna Uranium Company of Cortez, Colorado made a shipment consisting of 16 tons averaging 0.27 percent U_3O_8 and 1.07 percent V_2O_5 from a rim cut on the north end of Mesa I 1/2 (fig. 3, no. 9). Cuna believed they were mining on Henry Phillips MP-28 which was assigned to them on October 3, 1955. An investigation indicated the ore actually came from the adjacent MP-93 also held by Henry Phillips, but assigned to Kerr-McGee. On the southwest side of the mountains, Kerr-McGee began production at the Black No. 1 Mine (fig. 3, no. 47) on Flag Mesa (lease 8667) and at the Bare Rock Mesa Mine (fig. 3, no. 49) (also called the Black No. 2) on Koley Black's MP-239. Also on the southwest side, Price Exploration Company, Salt Lake City, Utah, began production at the Tommy James Mine (MP-109) on Fall Down Mesa (fig. 3, no. 44). During 1955, the Texas Mining Company, Austin, Texas, made a small shipment from their mine (fig. 3, no. 40) on Tom Nakai Chee's Mining Permit on Mexican Cry Mesa and Marcy Exploration and Mining Co., of Dolores, Colorado, began production from Nakai Chee Begay's MP-236 on Thirsty Mesa (fig. 3, no. 42).

During 1956, Kerr-McGee began production from three mines which would become very important as ore producers. A 300 foot long, minus 22 degree, inclined shaft on the east side of Mesa I 3/4 was known as the Mesa I 3/4 incline Mine (fig. 3, no. 12). Two adits at the head of the canyon separating Mesas I 3/4 and II on David Phillips' MP-21 were named the Mesa II P-21 Mine (fig. 3. no. 14), and an incline on the west side of Mesa II 1/2 was known as the Mesa II 1/2 Mine or incline (fig.3, no. 19). All three of these mines were planned to develop and mine ore that had been located by Kerr-McGee in offsetting AEC ore and/or mineralized drill holes. During 1956, Kerr-McGee reopened the Mesa IV No. 2 Mine (fig. 3, no. 25), on the east side of the tip of Mesa IV.

On the southside mesas, Price Exploration Co. made final shipments from the Tommy James Mine on Fall Down Mesa. E. D. Warren and Ralph Dye, Salt Lake City, Utah, began production at the Jimmie King No. 9 Mine (fig. 3, no. 43) on Navajo Chair Mesa as did W. Boyd Hall, Cortez, Colorado, at Tom Nakai Chee's MP-381 on Thirsty Mesa (fig. 3, no. 41). Walter Duncan completed mining on Willie Cisco's MP-13 and closed the Camp Mine on Camp Mesa in 1956.

In 1957, Climax Uranium Co. began shipping ore from the Frank No. 1 Mines to their mill at Grand Junction, Colorado, a distance of 337 miles. Kerr-McGee began mining on George Simpson's MP-181 which was located in the western part of Mesa IV 1/2. This ore body was reached from the mine workings of the Mesa IV 1/2 Mine (fig. 3, no. 32). A small amount of ore was mined at the new Mesa I 1/4 Mine (fig. 3, no. 7), and the Flag Mine, which began operating in 1953, was closed, as was the Bare Rock Mesa Mine which began in 1955.

The Nakai Chee Begay Mine (MP-236) on Thirsty Mesa was closed in 1957 by W. Boyd Hall, who took over the assignment of the mining permit in 1956. Hall continued to mine at the Hall Mine, (MP-381), also on Thirsty Mesa. Final shipments were made by E. D. Warren from the Jimmie King No. 9 Mine on Fall Down Mesa in 1957.

Production in 1958 took a sharp increase over 1957 when 337,440 pounds U_3O_8 were produced (Figure 7). The increase was due mainly to increased production at the Mesa II P-21 Mine and also at the Mesa IV Mine and clean up mining at the Mesa III Mine. A new mine on Mesa I 1/2 (fig. 3, no. 8) was briefly operated by Kerr-McGee. During the same year Kerr-McGee closed the Mesa III Mine which had been in operation since 1953 and the Mesa IV 1/2 Mine, which began production in 1954. Final shipments were made from the George Simpson MP-181 in 1958. Total production from MP-181, which was mined through the Mesa IV 1/2 Mine, was 994 tons that averaged 0.23 percent U_3O_8 and 1.67 percent V_2O_5. On the southside mesas, Boyd Hall closed the Hall Mine on Thirsty Mesa which was located on Tom Nakai Chee's mining permit.

Total production in 1959 was 295,317 pounds, a small decrease from 1958 (Figure 7). Although production increased at Kerr-McGee's Mesa I 3/4 incline Mine and at the Mesa II 1/2 Mine, production declined at the Mesa II P-21 and Mesa IV Mines and also at Climax's Frank No. 1 Mines. During the year, Kerr-McGee closed the Mesa IV No. 2 Mine for the second time, and Climax Uranium Co. began production from Billy Topaha's MP-22 at the head of the canyon separating Mesa I 1/2 and Mesa I 3/4 (fig. 3, no. 11). This production was shipped to the company's mill at Grand Junction, Colorado. On the southside, Boyd Hall reopened the Nakai Chee Begay Mine (fig. 3, no. 42) on Thirsty Mesa which he had closed in 1957.

Due to the fact that Cato Sells refused to pay the Navajo Tribe a royalty on his ore production, he lost control of his mining permits in the Lukachukais and elsewhere on the Reservation in August 1959. An area of 130 acres on the north side of Mesa V was claimed by Frank F. Junior (son of Frank Nacheenbetah) as MP-537 on October 1, 1959. This permit was assigned to Climax Uranium on November 17, 1959. Some 187 acres formerly held by Sells on Mesa VI was claimed by Peter Fred Yazzie as MP-548 on September 20, 1960, and was assigned to Kerr-McGee on October 26, 1960.

Production during 1960 reached an all-time yearly high when 87,065 tons averaging 0.23 percent U_3O_8 and 1.00 percent V_2O_5 and containing 404,948 pounds U_3O_8 and 1,739,793 pounds V_2O_5 were produced (Figure 7). Ten mines were active in 1960, but the Mesa II P-21 Mine produced nearly 80 percent of the total uranium. Here, production averaged about 5,600 tons-per-month with an average grade of 0.24 percent U_3O_8.

During 1960, Kerr-McGee began producing from a new mine on the western portion of Mesa V (fig. 3, no. 33). Two adjacent ore levels were reached via a 1,000 foot long, sublevel haulage drift. This deposit had been developed in the vicinity of some AEC mineralized drill holes. During the year, Kerr-McGee briefly reopened the Mesa IV 1/2 Mine (fig. 3, no. 32) which was adjacent to, and connected with the new Mesa V Mine.

Climax began mining in the abandoned underground Cato No. 1 Mine on Mesa V (fig. 3, no. 37), now claimed by Frank Junior. The ore was shipped to their mill at Grand Junction, Colorado. During 1960, Climax mined out and closed the Billy Topaha Mine between Mesa I 1/2 and I 3/4. The Nakai Chee Begay Mine on Thirsty Mesa was shut down by Boyd Hall in 1960.

Since tribal mining permits were issued for a period of two years and could be renewed for an additional two years, the Bureau of Indian Affairs urged the operators in the Lukachukais to convert their holding to leases, good for a period of ten years. During 1961 both Kerr-McGee and Climax Uranium made the conversion, however the old mining permit numbers were still used for several of the mines. David Phillips' MP-21 became lease 14-20-0603-6678 and the Estate of Dan Phillips' MP-150 became lease 14-20-0603-6514, Frank Nacheenbetah's MP-72 became lease 14-20-0603-6528.

In 1961, production declined to 314,855 pounds U_3O_8 (Figure 7) as monthly production rates declined at the Mesa II P-21 Mine and the Frank No. 1 and Frank Junior Mines. However production did increase in 1961 at the Mesa V Mine. New ore was discovered on Mesa I and the mines which closed in 1958 were reopened. Kerr-McGee also started a new mine on the south side of Mesa VI on Peter Fred Yazzie's MP-548 (fig. 3., no. 38). On May 11, 1961, Kerr- McGee acquired the assignment of Tommy James' MP-109 on Step Mesa and began to develop an ore body on the west side of that mesa.

Production in 1962 continued to decline as 277,661 pounds U_3O_8 were produced (Figure 7). This was largely due a continued decline at the Mesa II P-21 Mine. Production increased at the Mesa V Mine and Kerr-McGee began mining on Step Mesa (fig. 3, no. 45) and reopened the Mesa IV No. 2 Mine. By late 1962, the Mesa VI Mine, being operated by contract miners, was shut down. Robert H. Goode, a former contract miner for Kerr McGee at Mesa VI, took the assignment of Willie Cisco's MP-577 (formerly MP-13) on September 24, 1962, and began mining at the Camp Mine, which had been closed since 1956. The Frank Junior Mine on Mesa V, which was reactivated by Climax Uranium in 1960, closed in 1962.

Early in 1963, pending as acqusition by VCA, Kerr-McGee terminated mining by contractors at Mesa I and the Mesa II 1/2 incline Mine.

VCA - The Final Years

On March 1, 1963, the Vanadium Corporation of America (VCA) of Durango, Colorado took an option to acquire Kerr-McGee's Navajo Uranium Division, including their leases and mining permits, mill and employee housing in Shiprock. This acquisition was approved by the Bureau of Indian Affairs on July 29, 1963. While the final approval was pending, VCA closed their Durango, Colorado mill in April 1963 and all of the company controlled ore on the Colorado Plateau was then processed at Shiprock.

In the Lukachukai Mountains, VCA continued production at the Mesa I 3/4 incline, Mesa II P-21, Mesa V and Step Mesa Mines. They reopened the closed Mesa III, Mesa VI, and Bare Rock Mesa Mines and opened up two new small mines called Mesa II 1/4 (fig. 3, no. 18) and Mesa IV West (fig. 3, no. 27). Also, during 1963, Climax Uranium closed the mines on the Frank No. 1 lease. In the same year, James Hall made a final shipment from the Nakai Chee Begay Mine (MP-236) on Thirsty Mesa. Some 29 tons averaging 0.14 percent U_3O_8 and 0.43 percent V_2O_5 were produced from the adjacent Tom Joe MP-298, through the Begay Mine. In 1963 Robert Goode completed mining at the Camp Mine on Camp Mesa. Production in 1963 was 108,272 pounds U_3O_8, a substantial drop from 1962 (Figure 7). The Mesa II P-21 Mine which averaged 2,500 tons-per-month in 1962 dropped to 500 tons-per-month in 1963. The Mesa V Mine also dropped from 2,000 to 650 tons-per-month.

After acquiring the holdings of Navajo Uranium Division, VCA continued exploration drilling in the Lukachukais, but not of the magnitude done by Kerr-McGee. During 1963, VCA reopened the closed mines on Mesas I 1/2, II 1/2, IV, and closed the Mesa VI Mine and the mines on Step and Bare Rock Mesas. In 1964 total production from the mountains declined to 52,106 pounds U_3O_8 the lowest level since 1951 (Figure 7).

In 1965 production from the Lukachukais increased slightly to 58,686 pounds U_3O_8 (Figure 7). This was due to Climax reopening the Frank No. 1 Mines on Mesa IV 1/2. Also, some ore on the Frank Junior's MP-537 was produced through VCA's Mesa V Mine. During 1965, VCA closed the Mesa III Mine, but reopened, for clean up mining, some mines on Mesa I and the Mesa IV 1/2 Mine. A new small mine, Mesa IV 1/4 (fig. 3, no. 28) was started.

VCA opened up four new mines during 1966. Three small operations on the northeast mesas were named I 1/2 West, III Northwest, and III West (fig 3, nos. 10, 22, 23). On the south-side, a new mine was started on Knife Edge Mesa (fig. 3, no. 50). All of these mines would be mined out within the year. Mining continued by VCA at the Mesa I, Mesa I 1/2, Mesa I 3/4 incline, Mesa II P-21, Mesa II 1/2 incline, and Mesa V Mines as well as at Climax's Frank No. 1 Mines. Total production declined slightly in 1966 to 56,888 pounds U_3O_8 (Figure 7).

During 1967 production from the mountains declined sharply to 18,342 pounds U_3O_8 (Figure 7) as VCA mined out and closed the Mesa I, Mesa I 1/2, Mesa II P-21, and Mesa II 1/2 incline Mines. The large cluster of ore bodies mined from the Mesa II P-21 workings produced a total of 274,128 tons of ore that averaged 0.23 percent U_3O_8 and 1.00 percent V_2O_5 and contained 1,294,853 pounds U_3O_8 and 5,475,210 pounds V_2O_5 (Table 7). This amounted to 37 percent of the total uranium produced in the Lukachukais. The mine workings extended to the south and connected with the Mesa I 3/4 incline mine and to the northwest and joined the Mesa II 1/2 incline mine. Also in 1967, final shipments were made by Climax Uranium from the Frank No. 1 and Frank Junior Mines. The latter through VCA's Mesa V Mine. Mining continued at VCA's Mesa I 3/4 incline and Mesa V Mines.

By the spring of 1968, all mining had ceased in the Lukachukai Mountains. Early in the year, VCA closed the Mesa I 3/4 and Mesa V Mines, and did some final clean up mining at the Mesa IV 1/4 Mine. Total production in 1968 was 3,231 pounds U_3O_8. In the six years that VCA operated in the Lukachukai Mountains, the company produced 65,981 tons of ore that averaged 0.18 percent U_3O_8 and 0.80 percent V_2O_5.

During the 19 year period, 1950 through 1968, some 53 individual mines in the Salt Wash Member of the Morrison Formation, in the Lukachakai Mountains, produced 724,754 tons of ore that averaged 0.24 percent U_3O_8 and 1.02 percent V_2O_5 and contained 3,483,231 pounds U_3O_8 and 14,729,693 pounds V_2O_5. Details of the production, by individual mines are given in Table 3.

VCA was merged into Foote Mineral Company on August 31, 1967. Foote continued the Shiprock milling operation until May 1968 when the operations ceased. During the life of the mill, a total of 1,527,187 tons of ore averaging 0.26 percent U_3O_8 and 1.6 percent V_2O_5 and containing 7,895,893 pounds U_3O_8 and 35,376,092 pounds V_2O_5 were fed to process (Albrethsen and McGinley, 1982).

The millsite was returned to the Navajo Tribe in 1973. The plant was decommissioned, and the tailings stablized in 1986 by the Department of Energy under the Uranium Mill Tailings Control Act of 1978.

The preceding historical account of mining in the Lukachukai Mountains was compiled from many sources. The main sources were the monthly ore receipt reports sent to the AEC by the Shiprock mill, AEC buying station receipts, and records of the AEC's Circular 6 bonus program. Information on leases and mining permits provided by the Navajo Tribe's Mining Department at Window Rock, Arizona was extremely helpful. All of the above sources were supplemented with the author's personal observations during the 1950's and 1960's. Bill Stevens, a geological engineer with Kerr-McGee Navajo Uranium Division, reviewed the text for accuracy.

Table 3 was compiled by Elizabeth A. Learned from AEC production records and field notes, ore receipts from the Shiprock mill, and Bureau of Indian Affairs records. An initial version was included on a mine location map prepared by Chenoweth and Learned (1979). Production from Kerr-McGee's Mesa III Mine (fig. 3, no. 21) did not begin until 1954, yet the AEC records show a 1953 shipment by Hopkins and Smith. A review of the 1953 production records indicated that this 7 ton shipment, averaging 0.53 percent U_3O_8 and 2.91 percent V_2O_5, actually came from a Mesa 3 Mine in Mesa County, Colorado and was processed at the Climax Uranium Company's mill at Grand Junction, Colorado. Also, all years of production and the operators were checked for each mine and revised where necessary.

Table 3

Details of uranium-vanadium production, Lukachukai Mountains, Apache County, Arizona
(Revised June, 1988)

Index No.	Mine Name	Tons Ore	Pounds U_3O_8	$\%U_3O_8$	Pounds V_2O_5	$\%V_2O_5$	Period of Production	Operator
1.	Mesa I, Mine No. 13						1950-51	F.A. Sitton
2.	Mesa I, Mine No. 10						1951-52	Navajo Uranium
3.	Mesa I, Mine No. 15	58,082	382,755	.33	1,240,839	1.07	1953-58	Kerr-McGee
4.	Mesa I, Mine No. 11						1961-63	Kerr-McGee
5.	Mesa I, Mine No. 12						1965-67	VCA
6.	Mesa I, Mine No. 14							
7.	Mesa I 1/4 Mine	132	419	.16	2,078	.79	1957	Kerr-McGee
8.	Mesa I 1/2 Mine	7,555	33,436	.22	111,632	.74	1958 1964-67	Kerr-McGee VCA
9.	Henry Phillips Mine	16	85	.27	333	1.04	1955	Cuna Uranium
10.	Mesa I 1/2, West Mine	Minor production included with main I 1/2 Mine					1966	VCA
11.	Billy Topaha Mine	703	2,773	.20	13,502	.96	1959-60	Climax Uranium
12.	Mesa I 3/4 Incline	44,174	172,619	.20	788,005	.89	1956-63 1963-68	Kerr-McGee VCA
13.	Mesa I 3/4, Mine No. 2, P-150	6,423	32,365	.25	112,853	.88	1952-55 1959-61	Kerr-McGee Kerr-McGee
14.	Mesa II, Mines No. 1&2, P-21	274,128	1,284,853	.23	5,475,210	1.00	1956-63 1963-67	Kerr-McGee VCA
15.	Mesa II, Mine No. 1, P-150	3,825	20,241	.26	77,045	1.01	1952-55	Kerr-McGee

Table 3 (continued)

Index No.	Mine Name	Tons Ore	Pounds U_3O_8	$\%U_3O_8$	Pounds V_2O_5	$\%V_2O_5$	Period of Production	Operator
16.	Mesa II, Mine 4	36	272	.38	984	1.37	1952	Kerr-McGee
17.	Mesa II Pit	822	3,255	.20	9,970	.61	1950-51 1951	F.A. Sitton Navajo Uranium
18.	Mesa II 1/4 Mine	725	2,570	.18	12.275	.85	1963,1966	VCA
19.	Mesa II 1/2 Mine	38,343	186,723	.25	846,630	1.10	1956-63 1964-67	Kerr-McGee VCA
20.	Mesa II 1/2, Mine 4	114	606	.26	3,510	1.54	1952	Kerr-McGee
21.	Mesa III Mine	50,900	264,783	.26	1,239,741	1.22	1954-58 1963-65	Kerr-McGee VCA
22.	Mesa III, Northwest Mine	735	1,689	.12	8,826	.60	1966	VCA
23.	Mesa III, West Mine	Minor production included with N.W. Mine					1966	VCA
24.	Mesa IV, Mine No. 3	229	1,719	.38	4,178	.91	1953	Kerr-McGee
25.	Mesa IV, Mine No. 2	3,711	15,733	.21	68,375	.92	1950-51 1953-54 1956-59 1962-63	F.A. Sitton Kerr-McGee Kerr-McGee Kerr-McGee
26.	Mesa IV, Mine No. 1	7,648	37,320	.24	153,109	1.00	1950-51 1953,1955	F.A. Sitton Kerr-McGee
27.	Mesa IV, West Mine	3,365	12,578	.19	64,490	.96	1963	VCA
28.	Mesa IV 1/4 Mine	344	1,053	.15	7,949	1.16	1965,1968	VCA
29.	South Portal, Frank No. 1 Mine (4B Mine)						1951-57	Frank Nacheenbeta
30.	East Portal, Frank No. 1 Mine (709 Mine)	75,739	373,141	.25	1,738,347	1.15	1952 1957-63	Climax Uranium Climax Uranium
31.	North Portal, Frank No. 1 Mine (1207 Mine)						1965-67	Climax Uranium

Table 3 (continued)

Index No.	Mine Name	Tons Ore	Pounds U_3O_8	$\%U_3O_8$	Pounds V_2O_5	$\%V_2O_5$	Period of Production	Operator
32.	Mesa IV 1/2 Mine (1212 Mine)*	8,977	45,586	.25	284,304	1.58	1960-63 1963-68	Kerr-McGee VCA
33.	Mesa V Mine	55,599	216,868	.20	794,757	.72	1960-63 1963-68	Kerr-McGee VCA
34.	Mesa V Adit (Mine 1)	4,906	20,953	.21	135,000	1.38	1951-52	Navajo Uranium
35.	Mesa V Incline (Mine 2)						1953-55	Kerr-McGee
36.	Cato No. 1 Pit	54	307	.28	2,722	2.52	1951	Cato Sells
37.	Frank Jr. Mine (Cato No. 1)	10,519	64,131	.31	357,736	1.70	1951-53 1960-62 1965,1967	Cato Sells Climax Uranium Climax Uranium
38.	Mesa VI Mine	8,994	43,679	.24	201,390	1.12	1961-62 1964	Kerr-McGee VCA
39.	Cato No. 2 Mine	52	244	.23	1,589	1.53	1953-54	Cato Sells
40.	Mexican Cry Mine (Tom Nakai Chee No. 1)	57	196	.17	236	.21	1955	Texas Mining
41.	Hall Mine (Tom Nakai Chee No.6)	2,448	9,986	.20	15,831	.32	1956-58	W.B. Hall
42.	Nakai Chee Begay Mine **	428	1,213	.14	4,358	.51	1955-56 1956-57 1959-60 1963	Marcy Exploratic W.B. Hall W.B. Hall J.W. Hall
43.	Jimmie King No. 9 Mine	80	162	.10	398	.25	1956-57 1957	Warren and Dye E.D. Warren
44.	Tommy James Mine (Fall Down Mesa)	853	2,873	.17	13,567	.80	1955-56	Price Exploratic

Table 3 (continued)

Index No.	Mine Name	Tons Ore	Pounds U_3O_8	$\%U_3O_8$	Pounds V_2O_5	$\%V_2O_5$	Period of Production	Operator
45.	Step Mesa Mine	8,841	34,831	.20	76,698	.43	1962-63 1963-64	Kerr-McGee VCA
46	Flag No. 1 Mine	11,286	54,467	.24	227,708	1.01	1953-57 1964,1966	Kerr-McGee VCA
47.	Black No. 1 Mine (Flag No. 2)	1,407	4,928	.18	17,681	.63	1955	Kerr-McGee
48.	Black No. 2 Mine (West)	Minor production included with eastern mine					1955	Kerr-McGee
49.	Black No. 2 Mine (Bare Rock Mesa)	1,879	7,059	.19	39,720	1.60	1955-57 1963-64	Kerr-McGee VCA
50.	Knife Edge Mesa Mine	1,032	3,843	.19	10,249	.50	1966	VCA
51.	Joleo Mine	10,751	51,793	.24	209,994	.98	1952-54	Walter Duncan
52.	Cisco Mine	Minor production included with Camp Mine					1953	Walter Duncan
53.	Camp Mine	18,853	89,119	.24	355,874	.94	1953-56 1962-63	Walter Duncan Robert Goode
	TOTALS	724,754	3,483,231	.24	14,729,693	1.02		

* Includes production from Simpson 181 permit in 1957-58.

** Includes production from Tom Joe 298 permit in 1963.

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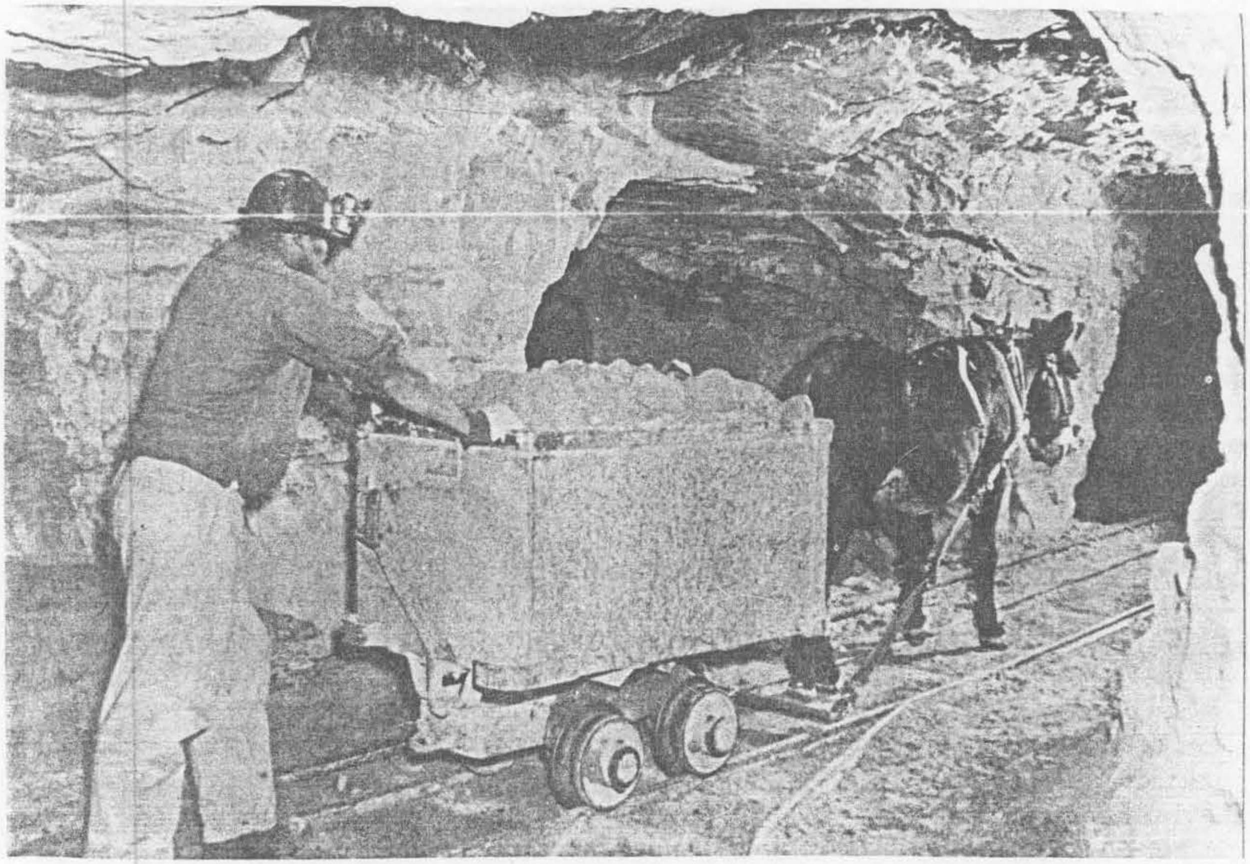

Figure 8, Navajo miner and burro tramming ore Frank No. 1 Mine. Photo by Dare (1959).

APPENDIX
Table 4

AEC reports resulting from exploration in the Lukachukai Mountains

Reports Published By The Technical Information Service, Oak Ridge, Tennessee

RME-27	Geology of the Uranium Deposits of the Lukachukai Mountains Area, Northeast Arizona, J. A. Masters, 1953, 23 p.
RME-44	Application of Cross Stratification Studies to Problems of Uranium Exploration, J. D. Lowell, 193, 17 p.
RMO-754	Geology and Ore Deposits of Mesa V, Lukachukai District, Arizona, J. W. King, 1951, 17 p.
RMO-802	Geology and Ore Deposits of Mesa VI Lukachukai District, Arizona, P. C. Ellsworth, and K. G. Hatfield, 1951, 12 p.
RMO-803	Geology and Ore Deposits of Mesa VII Lukachukai District, Arizona, J. W. King, and P. C. Ellsworth, 1951, 8 p.
RMO-911	Uranium Deposits on Southwest Rim of Lukachukai Mountain, Northeast Arizona, J. A. Masters, 1951, 10 p.

Reports Open-Filed by the Grand Junction Operations Office

RME-118	Geology of the Uranium Deposits of the Lukachukai Mountains, Apache County, Arizona, R. K. Nestler and W. L. Chenoweth, 1958, 64 p.
RME-184	Geology of Lukachukai Mountains Area, Apache County, Arizona, J. A. Masters, with a section on survey control by R. D. Blum, 1952, 50 p.
RME-199	Summary of Uranium Exploration in the Lukachukai Mountains, Apache County, Arizona 1950-1055, Contract Nos. AT(30-1) 1021, 1139, 1263, 1364 and AT(05-1) 234,257, R. F. Kosatka, 1956, 24 p.
RMO-629	Geology and Ore Deposits of Mesa V, Lukachukai District, Arizona, with Recommendations for Diamond Drilling, J. W. King, 1951, 15 p.
RMO-688	Geology and Ore Deposits of Mesa VI, Lukachukai District, Arizona, with Diamond Drilling Recommendations, P. C. Ellsworth and K. G. Hatfield, 1951, 9 p.

RMO-690	Geology and Ore Deposits of Mesa VII Lukachukai District, Arizona, J. W. King and P. C. Ellsworth, 1951, 7 p.
RMO-696	Results of Diamond Drilling on Mesas I, II, III, and IV, Lukachukai Mountains, Northeastern Arizona, H. W. Stafford, 1951, 15 p.
RMO-699	Geological Investigation of Mexican Cry Mesa, Lukachukai District, Arizona with Diamond Drilling Recommendations, P. C. Ellsworth, 1951, 8 p.
RMO-705	Uranium Deposits on Southwest Rim of Lukachukai Mountains, North-East Arizona, J. A. Masters, 1951, 12 p.
RMO-707	Uranium Deposits on Mesas I-1/2 and II-1/2, Lukachukai Mountains, Northeast Arizona, J. A. Masters and R. D. Blum, 1951, 8 p.
RMO-828	Drilling in the Lukachukai Mountains, Lukachukai No. 2 Project, Apache County, Arizona, M. E. Crew and J. D. Lowell, 1952, 60 p.
RMO-1011	Report on Examination of the Sitton Lease on the Navajo Reservation, Apache County, Arizona, S. K. Smyth, 1950, 8 p.
TM-37	Studies of Diamond Drilling at the Lukachukai No. 2 Project, L. Roberts, 1952, 8 p., (Engineering Report).
TM-97	A Preliminary Investigation of Triassic Rocks in the Lukachukai Mountains, Arizona, R. F. Kosatka, 1956, 10 p.
TM-107	Drilling in the Lukachukai Mountains, North Chuska Mountain Area, Apache County, Arizona, Contract No. AT(05-1)-234, J. W. Eppich, 1956, 9 p., (Engineering Report).
TM-110	Drilling in the Lukachukai Mountain Area, Apache County, Arizona, Contract No. AT(30-1)-1364, J. F. Brown, 1956, 6 p., (Engineering Report).
TM-115	Ore Occurrence Study, Mesa 4-1/2 Mines, Lukachukai Mountains, Apache County, Arizona, T. E. Beam, 1957, 7 p.
TM-143	Drilling in the Lukachukai Mountains, North Chuska Mountain Area, Apache County, Airzona, Contract AT(30-1)-1263, J. W. Eppich, 1957, 7 p., (Engineering Report).

TM-185 Causes of Color Variations in the Salt Wash & Recapture Members of the Morrison Formation on the Southside Mesas, Lukachukai Mountains, Apache County, Arizona, R. A. Laverty, 1954, 13 p.

TM-245 Drilling in the Lukachukai Mountains, Lukachukai No. 3 Project, Apache County, Arizona, R. L. Rock, 1954, 12 p.

RME - Raw Materials Exploration
RMO - Raw Materials Operations
TM - Technical Memorandum

Copies of the above reports can be obtained from:

Books and Open-File Reports Section
U.S. Geological Survey
P. O. Box 25425
Denver Federal Center, Building 810
Denver, Colorado 80225

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